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AN EXPERIMENTAL INVESTIGATION OF COOLING OF A LOW PRESSURE, LOW TEMPERATURE AIRSTREAM USING LIQUID AIR INJECTION

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ARO, Inc.

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ROCKET TEST FACILITY

ARNOLD ENGINEERING DEVELOPMENT CENTER

AIR FORCE SYSTEMS COMMAND

ARNOLD AIR FORCE STATION, TENNESSEE

NOTICES

LAZALIER

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FOREWORD

The work reported herein was done at the request of the Advanced Plans Division, Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under System 410L.

The results of the tests were obtained by ARO, Inc. (a subsidiary of Sverdrup and Parcel, Inc.), contract operator of AEDC, AFSC, Arnold Air Force Station, Tennessee, under Contract AF 40(600)-1200. The test was conducted in Propulsion Engine Test Cell (T-1) of the Rocket Test Facility (RTF) from July 22 to August 24, 1965, under ARO Project No. RA0542, and the manuscript was submitted for publication on November 5, 1965.

This technical report has been reviewed and is approved.

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ABSTRACT

An investigation was conducted to determine the feasibility of producing a low temperature, uncontaminated airstream by injection of liquid air into a primary airstream. Steady-state data were obtained with primary airflow conditions generally set at total pressures from 2.5 to 5 psia and supply air temperatures ranging from 380 to 540°R. Liquid airflow rates ranged from 0 to 13.5 lb/sec. Temperature drops of the primary airstream up to 85°R were recorded with liquid air-to-primary air ratios up to 0.146. Calculated cooling efficiencies ranged from 75 to 100 percent. Gas samples obtained in the mixing chamber at locations 10 and 24 ft downstream from the injection station indicated that the gas flow was a homogeneous mixture with the O_2 and N_2 content of the gas samples dependent upon the proportions injected.

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NOMENCLATURE

A	Area, in.^{2}
C_f	Flow coefficient
c_p	Specific heat at constant pressure, Btu/lb$_m$-°R
c_v	Specific heat at constant volume, Btu/lb$_m$-°R

D	Diameter, ft
g	Dimensional constant, 32.174 $ft\text{-}lb_m/lb_f\text{-}sec^2$
H	Enthalpy, Btu/lb_m
J	Mechanical equivalent of heat, 778.3 $ft\text{-}lb_f/Btu$
M	Mach number
P	Total pressure
p	Static pressure
R	Gas constant for air, 53.35 $ft\text{-}lb_f/lb_m\text{-}°R$
RF	Thermocouple impact-recovery factor
T	Total temperature
ΔT	Temperature differential
W	Weight flow, lb_m/sec
x	Axial length, ft
γ	Ratio of specific heats
η_c	Cooling efficiency, percent

SUBSCRIPTS

1, 1n, 2	Instrumentation stations
a	Air
i	Indicated
j	Jet
L	Liquid
LA	Liquid air
max	Maximum
min	Minimum
N_2	Nitrogen
O_2	Oxygen
th	Theoretical
v	Vaporization
wall	Wall

SECTION I
INTRODUCTION

Methods of providing testing capabilities for planned high-corrected-airflow airbreathing engines in relatively large test facilities such as the Propulsion Engine Test Cell (J-1) (Ref. 1) at the Arnold Engineering Development Center have been studied and are feasible. Testing capability at low air temperatures simulating the high altitude, low Mach number portion of an engine flight envelope is limited only by the cost and size of the mechanical refrigeration system. A cooling process using "liquid air" (LN_2 and LO_2 in the correct proportion) injected into the primary airstream has been suggested as an economical means of obtaining additional cooling for intermittent, short duration test periods.

A typical operational envelope for a high bypass ratio turbofan engine is presented in Fig. 1. The continuous testing capability of Test Cell (J-1) (including facility modifications in progress) for such a turbofan engine is presented in Fig. 2. Lines of constant mismatch temperatures are presented, with the zero mismatch line representing the cooling limitation of the mechanical refrigeration system (Ref. 2). Matched temperatures for the cruise range of the turbofan engine can be obtained by the addition of approximately 4300 tons of mechanical refrigeration to the existing plant capability (Ref. 1) with maximum mismatch of 30°R for off-design point operation within the envelope. The shaded area in Fig. 2 represents the region of liquid air injection into the J-1 primary airstream to provide the coldest temperatures required for ram air temperature simulation.

An experimental test program was conducted in Propulsion Engine Test Cell (T-1) (Ref. 1) with primary objectives to: (1) determine the feasibility of this cooling process, (2) establish and document the operating characteristics of a simple injection system, and (3) determine the effect of mixing lengths on temperature distribution and gas composition.

Testing was conducted in a constant diameter (7-ft) duct mixing chamber which represented a 34-percent scale model of the J-1, 12-ft-diam mixing chamber. Data were obtained at steady-state conditions with the primary airstream flowing at Mach 0.146, total pressures from 2.5 to 5 psia, primary air total temperatures from 380 to 560°R, liquid airflow rates from 0 to 13.5 lb/sec, and liquid air-to-primary air ratios from 0 to 0.146.

SECTION II
APPARATUS

2.1 TEST ARTICLE AND INSTALLATION

2.1.1 Mixing Chamber

The mixing chamber used in this test was the 38-ft-long, 7-ft-diam inlet air duct (Fig. 3) for the Propulsion Engine Test Cell (T-1) which is an open-circuit, continuous flow tunnel with a 12-ft-diam plenum and test chamber (Ref. 1). The 7-ft-diam inlet duct is covered with 6 in. of insulation (maximum specified heat loss of 0.045 Btu/hr/ft^2/°R for duct air temperatures ranging from 360 to 1035°R) over a 5-in. air space between the insulation material and the duct outer wall. A liner (Figs. 3a and b) was located downstream of the injection manifold to protect the cell wall from possible liquid impingement. A 42-in.-diam bellmouth was attached to the test cell plenum bulkhead (Fig. 3a) for airflow measurement.

2.1.2 Cryogenic System

The cryogenic supply system consisted of separate liquid nitrogen and liquid oxygen run tanks, an LO_2/LN_2 blender, and a liquid air injection system (Fig. 4). Both run tanks were pressurized with gaseous nitrogen. The LN_2 run tank was double walled and insulated. The flow line from this tank to the blender was 3 in. in ID, approximately 32 ft long, and was covered with 2-in.-thick fiber glass insulation and a vapor barrier jacket. The two LO_2 run tanks were single walled and uninsulated. The 1.5-in.-ID flow line from these tanks to the blender was approximately 34 ft long. The LO_2 flow line inside the barricade (approximately 23 ft long) was not insulated; the remainder was insulated similarly to the LN_2 line.

The liquid oxygen and liquid nitrogen flows were directed to a blender (Figs. 4 and 5) which mixed the two fluids to produce "liquid air." The liquid air flowed from the blender through a 3-in.-ID pipe, approximately 45 ft long, to the injection station in the mixing chamber (Figs. 3 and 4). This line was insulated similarly to the LN_2 line and was sized to handle liquid airflows up to 40 lb_m/sec.

The liquid injection system (Figs. 3b and 4) was designed to inject liquid air into the primary airstream to provide cold air at a downstream measuring station. The liquid injection station was located approximately 26 ft upstream of the mixing chamber exit plane. A 3-in.-ID pipe

was formed into a circular manifold having an OD of 45 in. Nipples were attached to the downstream side of the manifold for mounting 1-7G25 fog-jet nozzles (Figs. 3b and 6) with their orifices pointed downstream. The nozzles required that a 15- to 20-psi drop be maintained across the orifices to ensure atomization. Each nozzle head had seven 0.175-in.-diam orifices. The temperature data reported herein were obtained with five nozzle heads, each operated with four orifices open (Fig. 6). The manifold was insulated with wraparound asbestos insulation and glass tape.

2.2 INSTRUMENTATION

Diagrams showing details of the quantity and type of duct instrumentation at each station location are presented in Figs. 7 and 8. Design details of the pressure and temperature probes are presented in Fig. 9.

The flow evaluation instrumentation rake (station 1n) provided for the measurement of total pressures, total gas temperatures, and gas compositions. This rake was located either 10 or 24 ft downstream of the injection station.

Except for four copper-constantan immersion-type thermocouples located in the injector manifold, all temperatures were sensed by iron-constantan (IC) thermocouples. Sonic aspirating thermocouples were used at stations 1 and 1n, and radiation shielded thermocouples were used at station 2. The millivolt outputs of these thermocouples were recorded on magnetic tape by a multichannel, analog-to-digital converter system. Stations 1 and 1n thermocouples were equally spaced along the duct diameter, whereas the station 2 thermocouples were located between the total head pressure probes.

Eight bare IC thermocouples were peened into the duct wall surface (four inside and four outside) approximately 7, 17, 24, and 28 ft downstream of the injector manifold. The millivolt outputs of these thermocouples were recorded on a null-balance potentiometer.

Cryogenic pressures (Fig. 4) were sensed with close-coupled, strain-gage-type transducers and recorded on continuous, direct-inking, null-balance potentiometers (strip charts). Cryogenic and airstream temperatures were also recorded on strip charts or on a photographically recording, galvanometer-type oscillograph.

Steady-state aerodynamic pressures were photographically recorded from manometer boards. The total head pressure probes at stations 1

and 1n were equally spaced along the duct diameter. The total head pressure probes at station 2 were located at the centers of equal areas.

Liquid nitrogen and liquid oxygen flow rates were measured using two turbine-type flowmeters in each of the supply lines. The outputs of these meters were recorded in digital form on a magnetic tape system. The flowmeters were laboratory calibrated using water, and the indicated flow rates were corrected for differences in liquid densities.

The gas sampling probes at station 1n were similar to the total head pressure probes (Fig. 9b). Gas was continuously extracted from the airstream through copper lines approximately 24 ft long by means of a vacuum source, and samples were collected in metal bottles (Fig. 10) located external to the air duct. A laboratory gas chromatograph indicated the O_2 and N_2 content by volume. Accuracy of the gas analysis is ±0.5 percentage points of the readings (this represents an accuracy of approximately ±2.4 percent for the O_2 content and ±0.64 percent for the N_2 content).

The instrumentation ranges, recording method, and system accuracies for parameters measured during the test program are presented in Table I.

SECTION III
PROCEDURE

3.1 PRIMARY AIRSTREAM SETTING CONDITIONS

Conditioned dry primary air was supplied to the mixing chamber at total pressures from 2.5 to 5 psia with inlet air temperatures from 380 to 540°R. The pressure ratio across the bellmouth was maintained such that the bellmouth was choked; the mixing chamber Mach number was thus fixed at approximately 0.146 (one-dimensional, isentropic, compressible flow value).

3.2 CRYOGENIC SYSTEM SETTING CONDITIONS

The LN_2 run tank valve was opened in measured increments for chill down of the system until LN_2 was flowing to the injection manifold. The same process was repeated with LO_2 to chill down the line from the LO_2 tanks to the blender. Then LN_2 and LO_2 were flowed together; the tank pressures were varied to give the desired liquid airflow rate with the desired LN_2/LO_2 proportion.

Dry air is a mixture consisting principally of nitrogen, oxygen, and argon with traces of other gases. The composition and major constituents of standard air are listed in Ref. 3. The desired composition for "liquid air", as manufactured and used in this report, was 76.9-percent LN_2 and 23.1-percent LO_2, by weight. Testing reported herein which resulted in cooling was limited to liquid airflows from 7.0 to 13.5 lb/sec, and the corresponding liquid air-to-primary air ratio, W_{LA}/W_{a1}, was varied from 0.05 to 0.146. Data were also recorded with zero liquid airflow at each test condition and occasionally with LO_2 or LN_2 flowed separately. All testing and data recording were at essentially steady-state conditions with liquid flows held constant for at least 25 sec.

Liquid nitrogen flow rates were obtained by varying the LN_2 tank pressure from 40 to 60 psia. Liquid oxygen flow rates were obtained by varying the LO_2 tank pressure: 1) from 50 to 60 psia with downstream valve open or 2) from 80 to 175 psia and throttling with the downstream valve.

The thermodynamics of the air injection system is discussed in Appendix I. The methods of calculations are presented in Appendix II.

SECTION IV
RESULTS AND DISCUSSION

An investigation was conducted in a 7-ft-diam duct mixing chamber to determine the feasibility of liquid air injection into a primary airstream flowing at Mach 0.146: to provide uncontaminated low temperature air, to establish and document the operating characteristics of a simple injection system, and to determine the required mixing lengths for uniform flow characteristics. Flow characteristics were determined at two measuring stations, 10 and 24 ft downstream of the injection station. Cooling efficiency, total temperature drop, typical temperature profiles and distortion levels, and gas analysis are presented. Recorded air temperature differentials were corrected for duct wall heat source effects (Appendix II).

4.1 AIRSTREAM COOLING

Variations of recorded temperature drops (ΔT) between stations 1 and 1n are presented in Fig. 11 as a function of the inlet air temperature and the liquid air-to-primary airflow ratio, W_{LA}/W_{a1}, at two locations of the station 1n measuring rake. Also included for comparison

are lines of theoretical temperature drops for 100-percent cooling efficiency, η_c. Variation of W_{LA}/W_{a1} was accomplished primarily by varying the primary air pressure. Temperature drops up to 85°R were obtained (Fig. 11b).

Thermodynamic theory predicts that an increase in tank pressure results in a slight reduction in the expected temperature drop (Appendix I). The ΔT's obtained with high LO_2 tank pressures were in close agreement with those obtained with low LO_2 tank pressures and were found to closely approximate the theoretical values.

The cooling efficiencies, η_c, are presented in Fig. 12. The calculated η_c values fell within an overall band ranging from 75 to 100 percent. There were no discernible trends with mixing chamber length or with primary air temperature.

The minimum liquid airflow rates obtainable with the system used (due to system operational characteristics) produced temperature drops in the mixing chamber higher than those required for the region of interest in the turbofan engine operational envelope (Fig. 2). Therefore, testing with higher primary air temperatures (greater than 430°R) was included. The resultant air temperatures are presented in Fig. 13 and show that the mixing chamber exit temperature can be controlled with liquid air injection to correspond to the ram air temperature requirements for turbofan engine testing.

To determine the effect of moisture, a test run was included in the test program using primary air with moisture content ranging from 23 to 96 grains of water per pound of dry air. The test results were similar to those obtained with dry air. Visual and photographic observations of the flow exiting from the bellmouth with a blunt body in the near critical velocity airstream revealed that the airflow was heavily misted, but without apparent accumulation of ice or snow on the blunt body.

4.2 MIXING LENGTH

With no liquid air injection, the temperature distribution was generally flat in the core with the major variations near the wall; these temperature variations increased with decreasing air temperature, as expected.

Typical radial temperature profiles with liquid air injection obtained at 10 and 24 ft downstream of the injection station are presented in Fig. 14. The profiles improved as the gas mixture flowed downstream in the mixing

chamber with most of the distortions occurring near the wall. The profiles for the six arms were very similar, indicating that the circumferential temperature distributions were generally flat.

The variation of the maximum spread in the mixing chamber total temperature readings, expressed as a distortion factor, is presented in Fig. 15 as a function of the dimensionless mixing length parameter, x/D_j (Appendix II). The trend of the extrapolations of the data in Fig. 15 was determined by the application of the method of Ref. 4. Also included in Fig. 15 as a base for comparison and to determine mixing lengths required for the best obtainable temperature profile is a base line which represents the distortion obtained with no liquid air injection (primary air only). Since the primary-air-only distortion is a function of the air temperature, only the range of distortion values at 430°R is presented. The temperature distortion data cannot be used directly to determine the minimum mixing length. Analysis of the test data in Fig. 15 indicates minimum x/D_j's of approximately 120 to 180. For the test conditions reported herein, a typical value of D_j was 0.33 ft. Therefore, typical minimum mixing lengths of from 40 to 60 ft would be expected to be sufficient to establish a temperature profile equivalent to that without liquid air injection for this simple injection system.

The length of the initial portion of the distortion curve is a function of the injection configuration; this length may be shortened by improving the atomization of the liquid and by increasing the injection flow relative velocities (includes upstream injection). The slope of the distortion curve in Fig. 15 is primarily a function of the turbulence level in the primary flow and can be increased by various means. Thus, it is seen that the mixing lengths determined by this investigation could be greatly reduced, both by improving initial distribution and by causing faster mixing by means of mechanical mixing aids.

The injection of liquid air increased the airflow and decreased the airstream temperature in the mixing chamber. The resultant effect was that the chamber inlet and exit pressures were very similar, with negligible change in the axial pressure level throughout the duct. Also, the radial pressure profiles across the chamber were generally flat.

4.3 GAS SAMPLING

The O_2 and N_2 concentrations of all gas samples obtained during steady-state testing are presented in Table II. Also included in Table II are the predicted O_2 contents of the samples based on the liquid mass addition from the injector. Except for an occasional sampling by both

vertical arms (10 samples), sampling probes were selected at random, and only a few samples were taken at any one test condition.

Any deviation in the liquid flows from the correct LO_2/LN_2 proportion will affect the constituents of the gas mixture. Flows of LO_2 and LN_2 varied as much as from +6 to -9 percentage points, by weight, from the desired levels. Since the latent heats of vaporization for LO_2 and for LN_2 are very close to that for liquid air, these variations in the individual liquid flows showed negligible effects on the cooling process and the resultant temperature drops recorded at station 1n.

Because of flow deviations, determination of gas distribution is based on the ratio of actual O_2 content in the gas sample to the predicted O_2 content. The O_2 contents of the sampled primary air (Table II) show some scatter but are within the ±2.4 percent accuracy for O_2 readings from the gas chromatograph. With liquid airflow, 83 percent of the O_2 content ratio data population fell within a ±2.5 percent band, and 93 percent fell within a ±4 percent band (this represents the accuracy range of the gas chromatograph and flowmeter measurements). The ±4 percent accuracy band corresponds to an O_2 content variation of 20.1 to 21.8 percent, by volume, for injection of ideal liquid air into the primary airstream. There was no noticeable trend with sampling rake location or liquid flow rate.

Typical gas sample profiles across the mixing chamber with the rake located at the 24-ft position are presented in Fig. 16. The profile improved with increasing mixing chamber pressure (as liquid air-to-primary air ratio was decreased), as expected. The small spread in the O_2 data in Fig. 16 and Table II indicates that the gas mixture in the mixing chamber was essentially a homogeneous mixture of air constituents with negligible stratification.

With the instrumentation available, mixing performance and efficacy of the blender could not be determined and/or evaluated. The gas sampling results indicate that the complete supply flow line system (from blender to injector manifold) functioned to mix the LO_2 and LN_2 fluids to produce liquid air in a continuous manner.

4.4 EQUIVALENT MECHANICAL REFRIGERATION

Figure 17 shows the specific equivalent mechanical refrigeration (SEMR) for the test results shown in Fig. 11. Values of SEMR varied from 30 to 42 tons/lb_m/sec of liquid air and indicated a slight increase with increasing exit temperature, as expected.

The highest liquid air-to-primary air ratio achieved in this test was 0.146 (primary airstream of 92.5 lb_m/sec and a liquid airflow of 13.5 lb_m/sec), resulting in a maximum temperature drop of 85°R, an η_c of 98 percent, and a SEMR of 42 tons/lb_m/sec. To have provided the same temperature decrease with mechanical refrigeration would have required a capability of 566 tons. Initial capital investment costs for a similar liquid air injection system are approximately $40,000. By assuming a typical refrigeration cost of $800 per ton, a $453,000 refrigeration equipment investment would have been required to provide the same cooling capacity. This is an order of magnitude higher than that required for the liquid air system. based on short duration operation

To obtain a Δt of 30°R with a primary airflow of 500 lb_m/sec for turbofan engine testing in Test Cell (J-1) (Fig. 2) would require approximately 25 lb_m/sec of liquid airflow. Assuming an average SEMR of 36 tons/lb_m/sec from Fig. 17, 900 tons of additional mechanical refrigeration at an initial capital investment cost of approximately $720,000 would be required to provide the same cooling capacity.

It should be noted that the liquid system reported herein was operated at the lower end of the liquid flow regime as dictated by the turbofan engine temperature envelope. If testing had been accomplished with the maximum possible liquid flow, approximately 40 lb_m/sec, the equivalent mechanical refrigeration and costs would have been increased proportionally, whereas the initial cost of the liquid air injection system would remain the same. Thus for short duration, intermittent testing and/or short term cooling, the liquid air process would require considerably less capital investment than mechanical refrigeration.

4.5 OPERATIONAL CHARACTERISTICS AND DIFFICULTIES

During the cryogenic checkout period, it was determined that the minimum liquid air that could be flowed and still remain liquid (or two phase fluid) at the injector manifold inlet (as indicated by entrance thermocouple) was approximately 6.6 lb_m/sec. This flow rate limit was due primarily to the residence time of the liquid in the 3-in. pipe and/or to the heat transfer across the pipe from ambient conditions.

The injector manifold thermocouple located 180 deg from the liquid air inlet line and the thermocouple located at the top of the manifold (Fig. 4) indicated fluid temperatures approximately 40 deg higher than the manifold entrance and bottom thermocouples. These temperature differentials indicate that some orifices were injecting liquid (or two phase fluid) while others were injecting gas, thus contributing to the

temperature profiles at station 1n and affecting the resultant mixing length. Evaporation within the manifold could be prevented or retarded to ensure liquid flow to all orifices by use of a multiple cross-feed system (to introduce liquid at several stations of the manifold with one entry at the highest point in the manifold) and/or efficient insulation of the manifold.

The LO_2 tank pressure was operated in two modes to produce the desired flow rates. In the first mode the valve downstream of the flowmeter was opened wide, and the tank pressure was varied from 50 to 60 psia thereby controlling flow rate. In this mode, cavitation was experienced at the first LO_2 flowmeter which caused erroneous flow measurements at the second flowmeter. To prevent cavitation at the flowmeters, tank pressures were varied from 80 to 175 psia, and the desired flow rate was obtained by throttling with the downstream valve.

Variation in LO_2/LN_2 proportion from the desired flow indicated the degree of difficulty in simultaneously setting the LO_2 and LN_2 flowrates to the blender and at the same time maintaining the resultant mixture in a liquid state at the injector for a sufficient length of time (25 sec) to record test data under steady-state conditions with the cryogenic system employed. The difficulties of flowing correctly proportioned liquid air are inherent in the system. These difficulties can be attenuated or completely removed by improvement in the system or flow procedure with manual operation or by use of automatic controls for proportional flow and/or for setting of tank pressures.

SECTION V
SUMMARY OF RESULTS

The results obtained during the evaluation of liquid air injection cooling of a primary airstream flowing at Mach 0.146, air pressures from 2.5 to 5.0 psia, and at air temperatures of approximately 430°R are summarized as follows:

1. The method of supplementing existing refrigeration equipment with a liquid air injection system is feasible.
2. Temperature drops of the primary airstream up to 85°R were recorded. Calculated cooling efficiencies fell within an overall band ranging between 75 and 100 percent.
3. Temperature distribution profiles improved as the gas mixture flowed downstream in the mixing chamber. Analysis of

test data obtained at 10 and 24 ft downstream from the injection station indicates the minimum mixing lengths were approximately 40 to 60 ft for this simple injection system.

4. Gas samples obtained from the mixing chamber indicated that the system functioned to mix LO_2 and LN_2 fluids to produce liquid air in a continuous manner and that the resultant gas flow was a homogeneous mixture with the O_2 and N_2 contents of the gas samples dependent upon the deviation from the correct O_2-N_2 proportion of the injected liquid air.

5. Liquid air injection had negligible effect on the pressure level and pressure profile throughout the mixing chamber.

6. For intermittent, short duration cooling in the range of 1000 tons, the initial capital investment for a liquid air system appears to be an order of magnitude lower than that for an equivalent mechanical refrigeration system.

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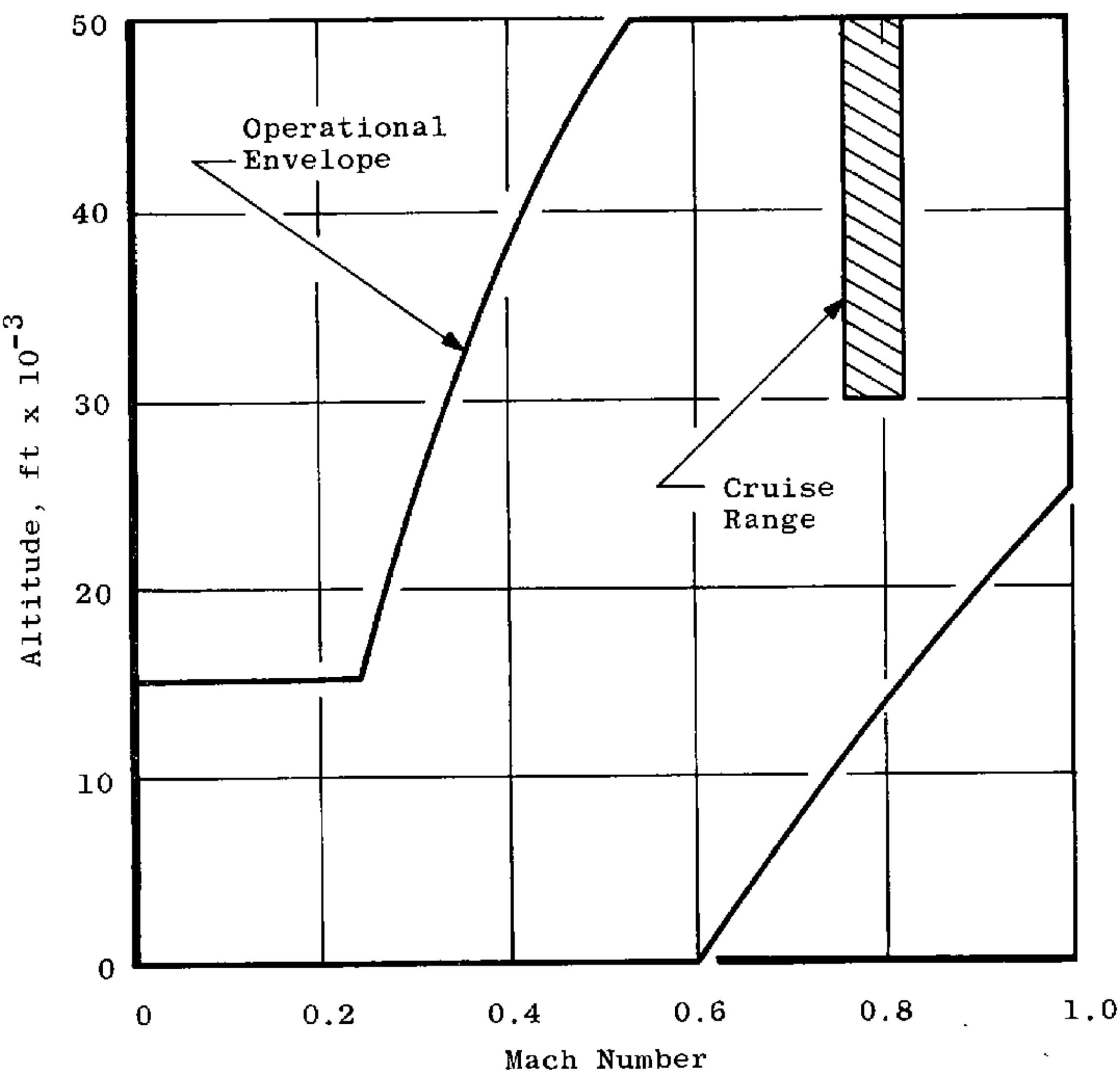
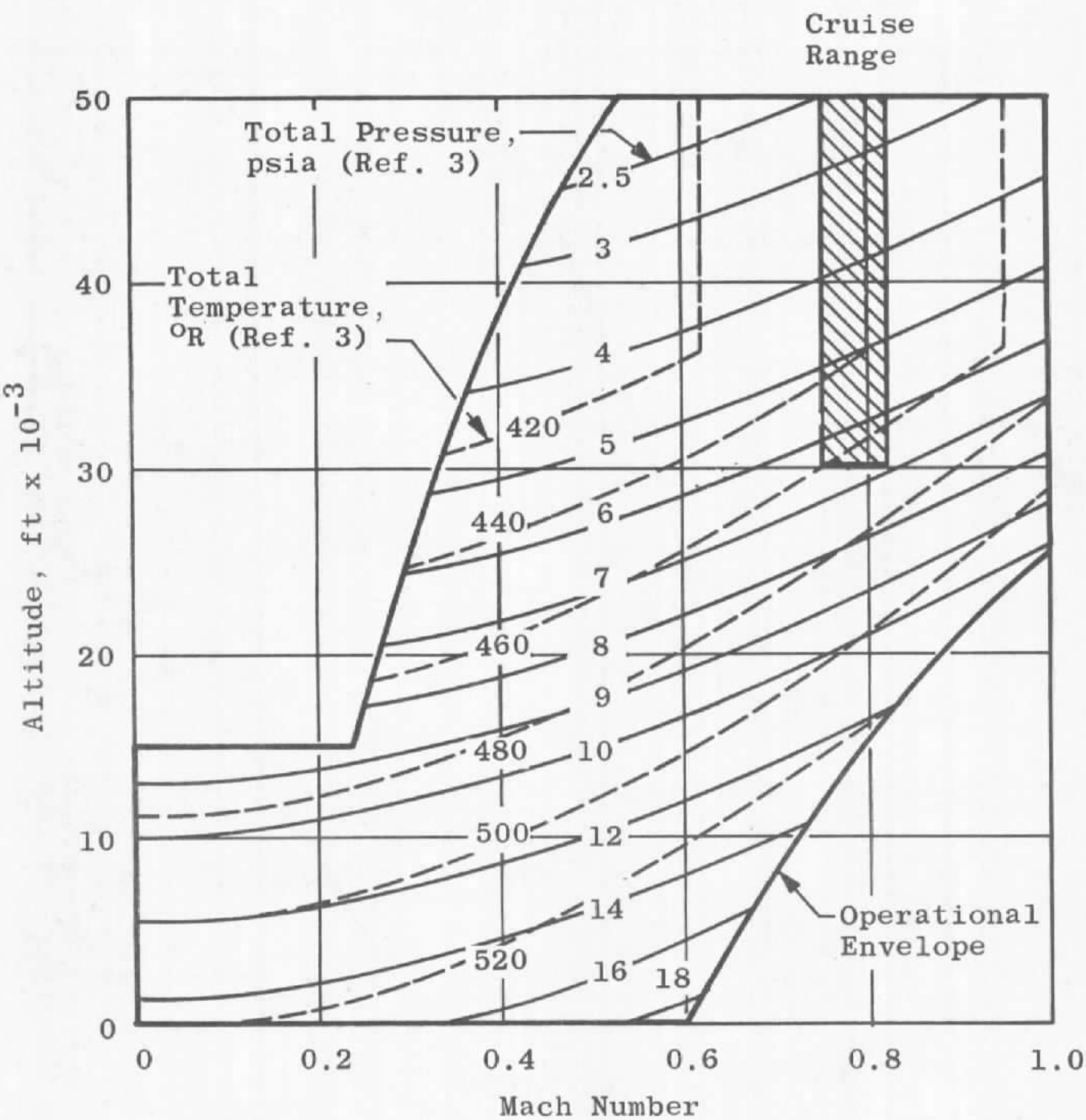


a. Envelope

Fig. 1 Typical Operational Envelope and Operating Conditions for a High Bypass Ratio Turbofan Engine



b. Inlet Total Pressure and Temperature

Fig. 1 Concluded

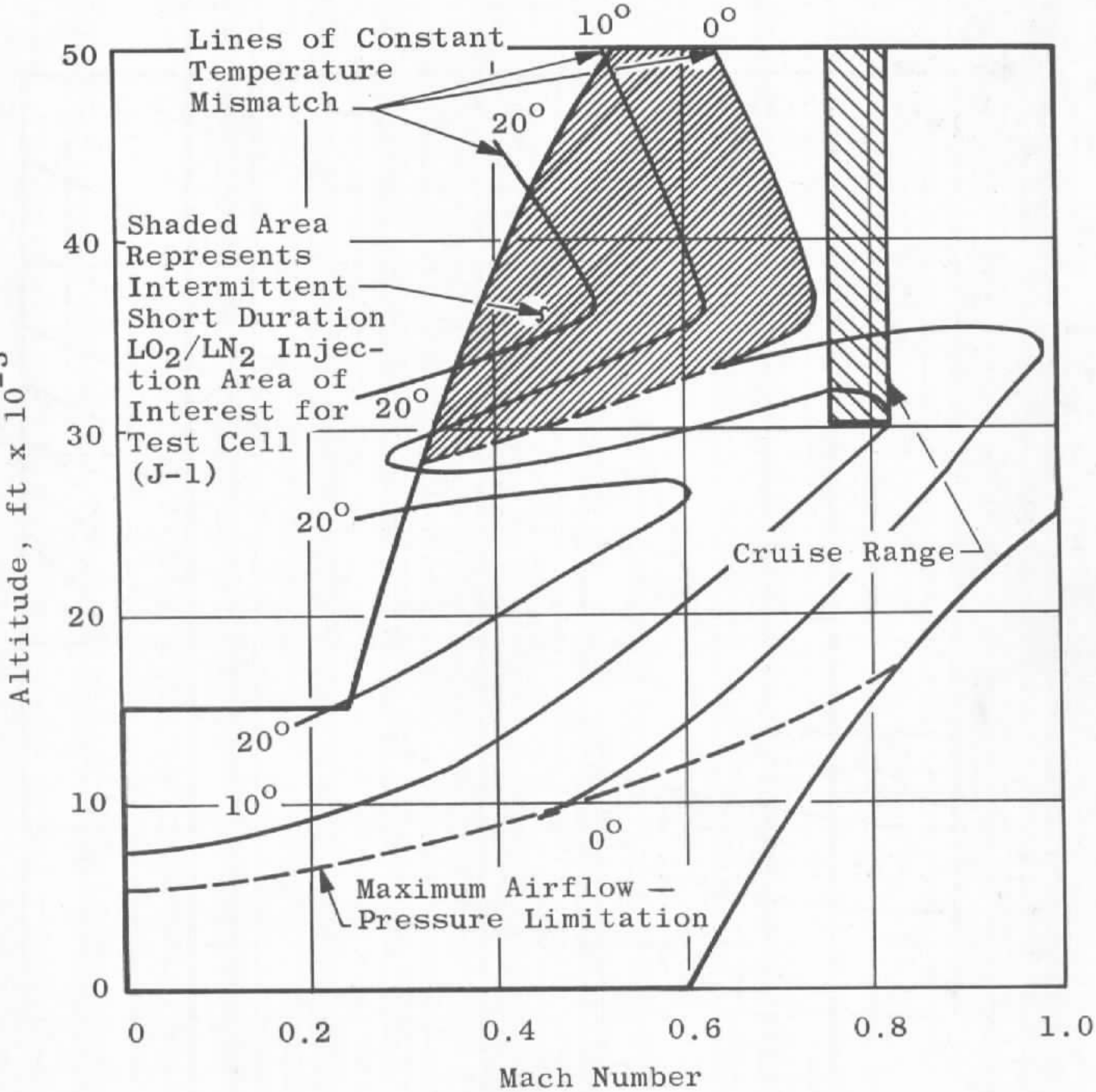
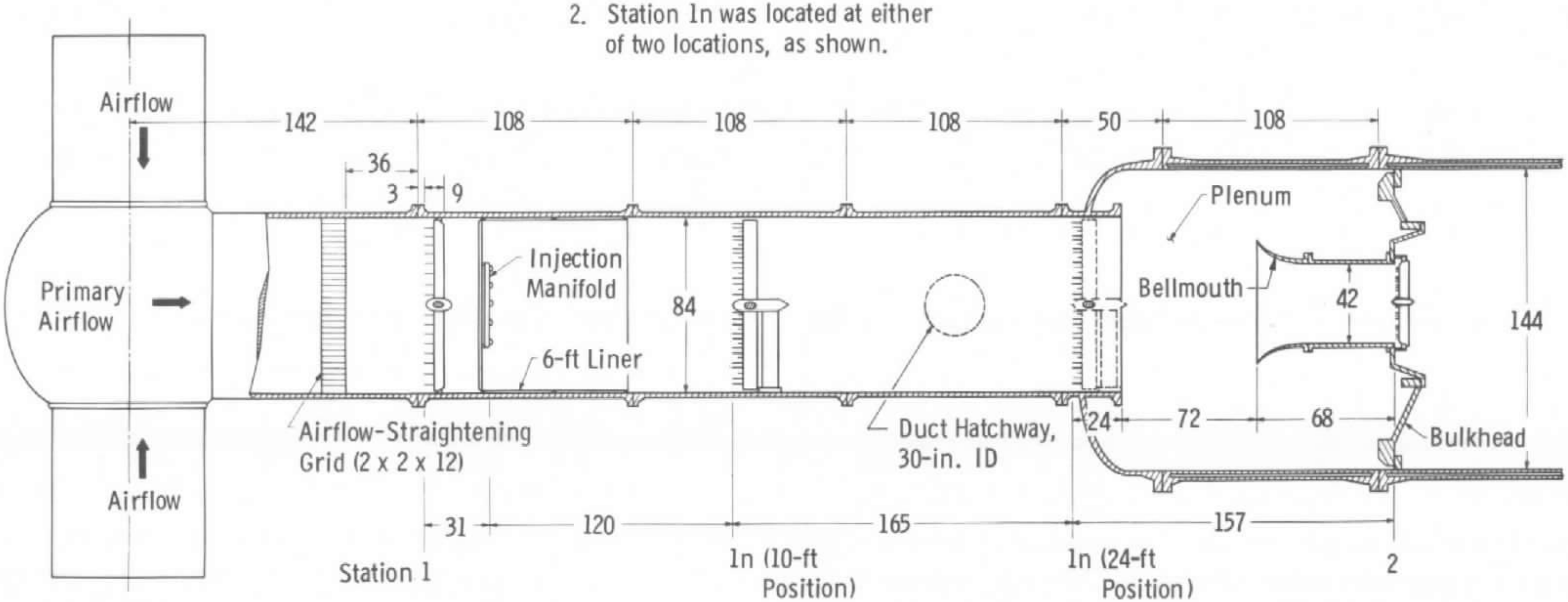


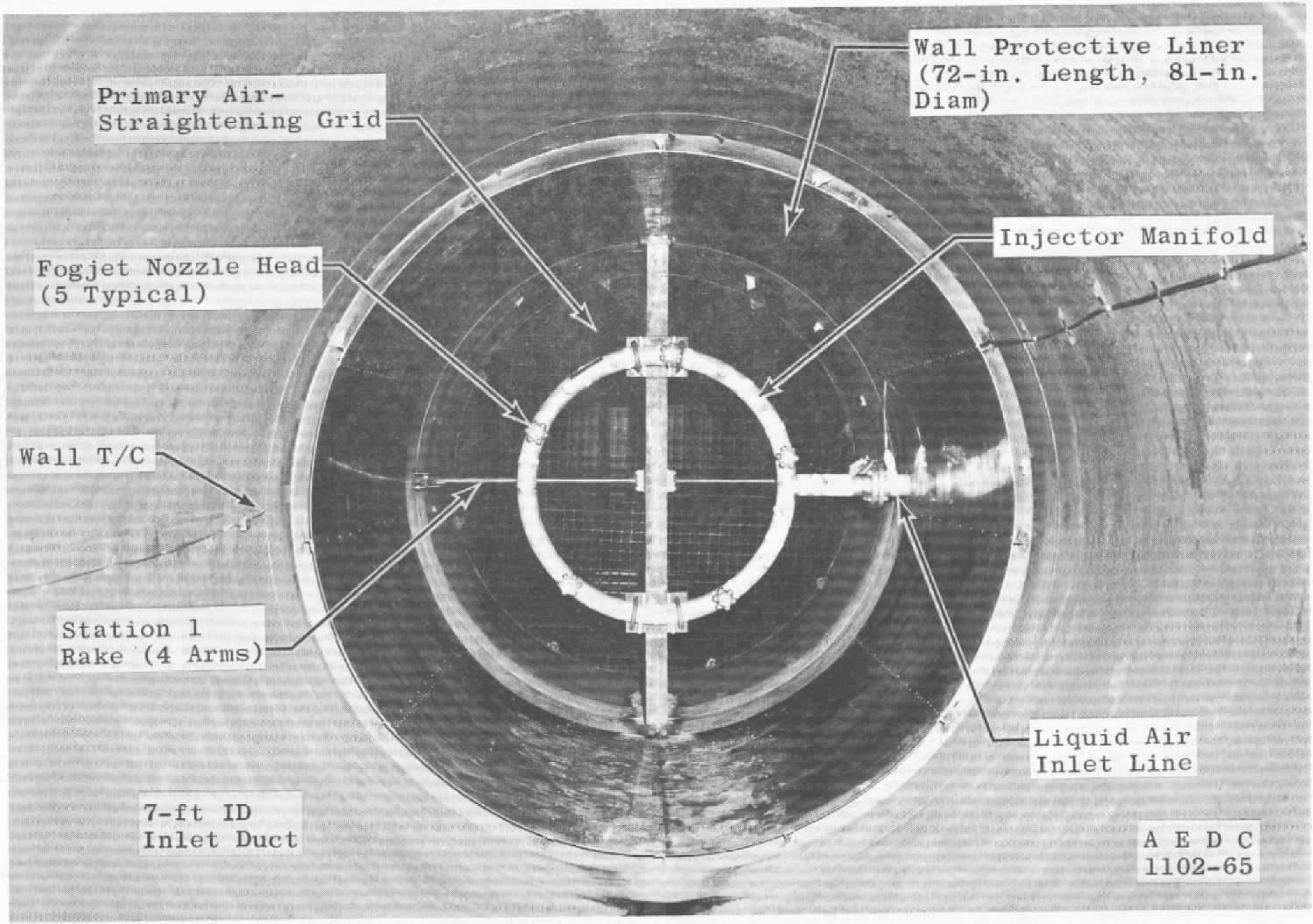
Fig. 2 Temperature Matching Capabilities for Flight Conditions in Propulsion Engine Test Cell (J-1)

Note: 1. All dimensions are in inches.
2. Station 1n was located at either of two locations, as shown.



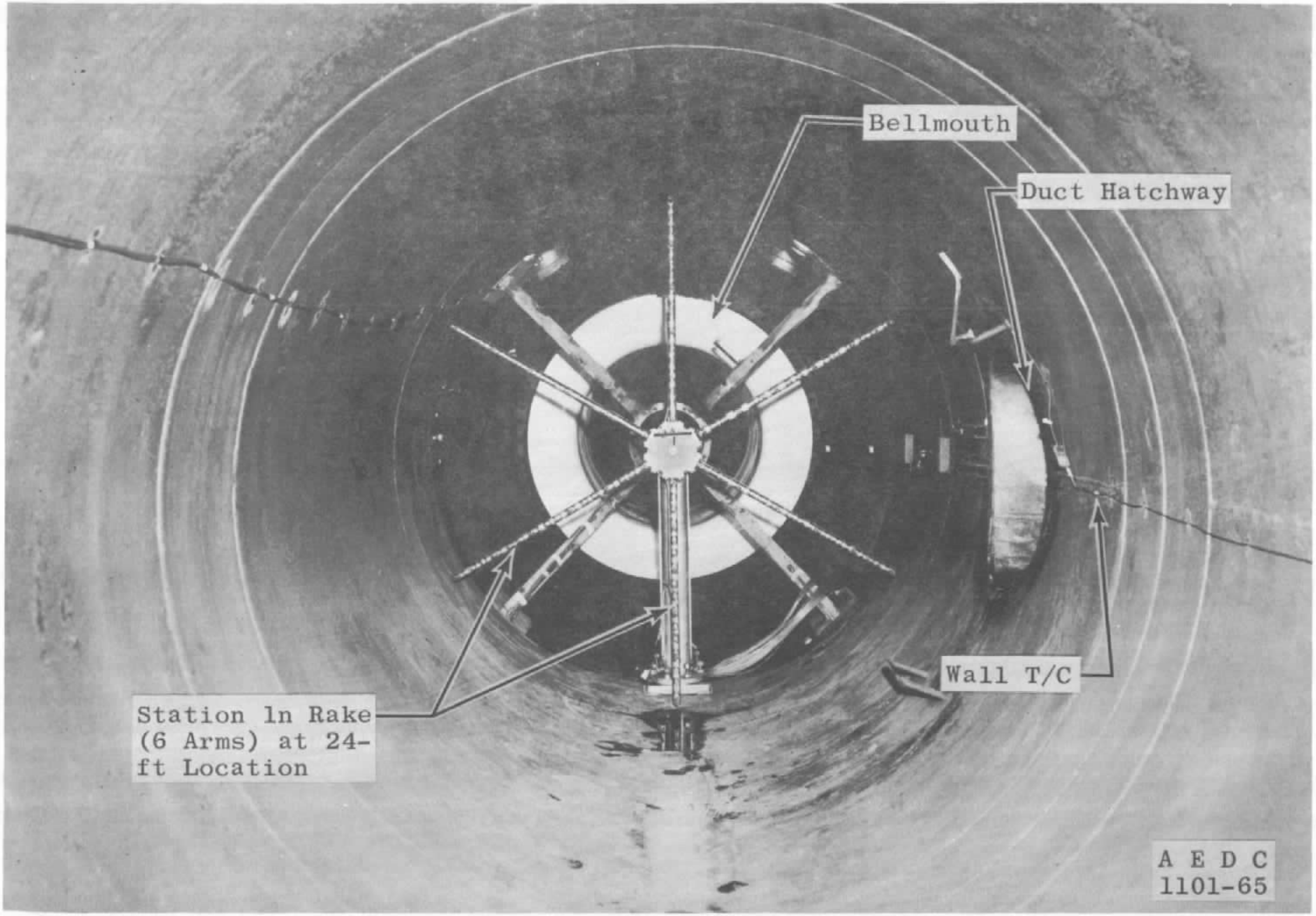
a. Schematic

Fig. 3 Inlet Air Duct to Propulsion Engine Test Cell (T-1)



b. Internal Photograph (Looking Upstream)

Fig. 3 Continued



c. Internal Photograph (Looking Downstream)

Fig. 3 Concluded

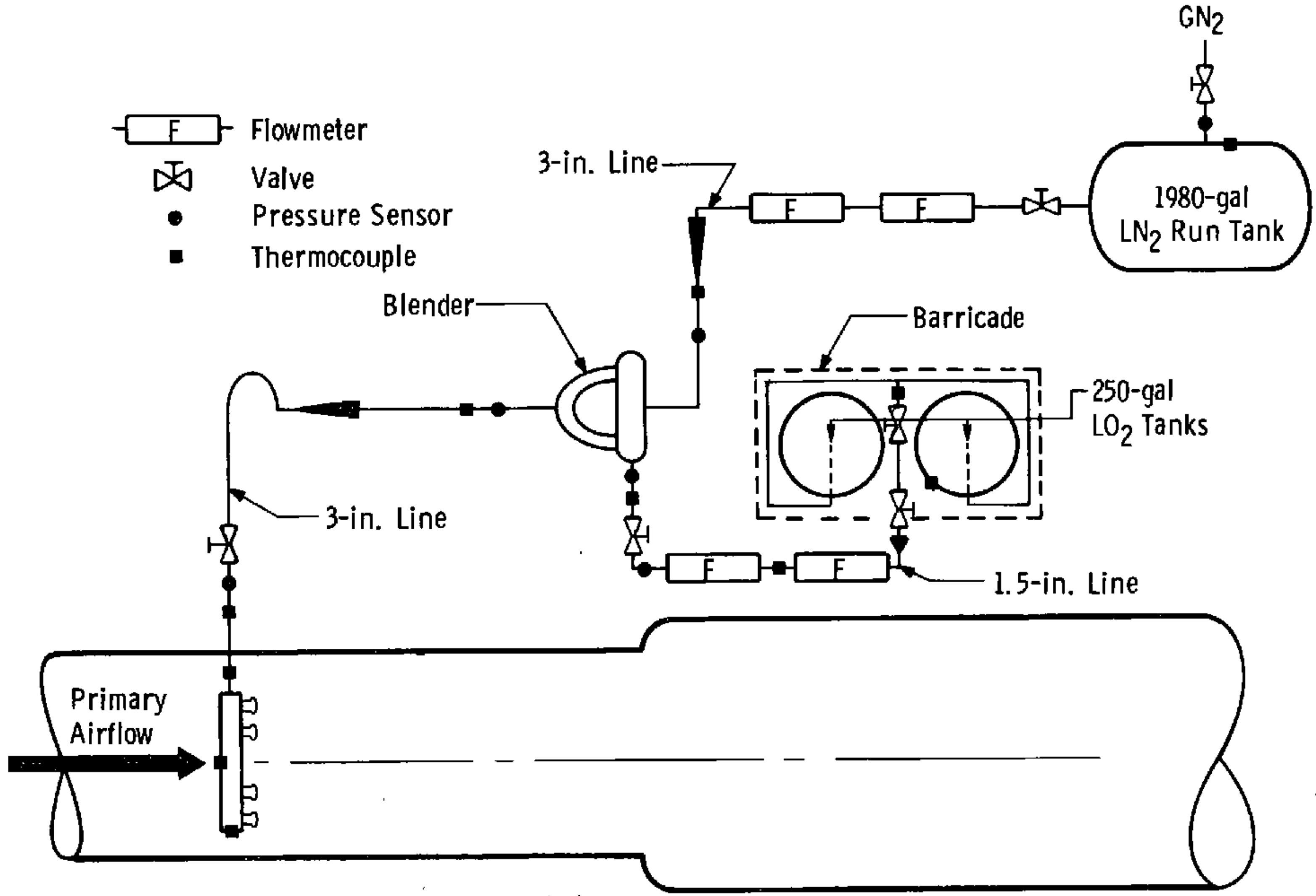


Fig. 4 Cryogenic Supply System Schematic

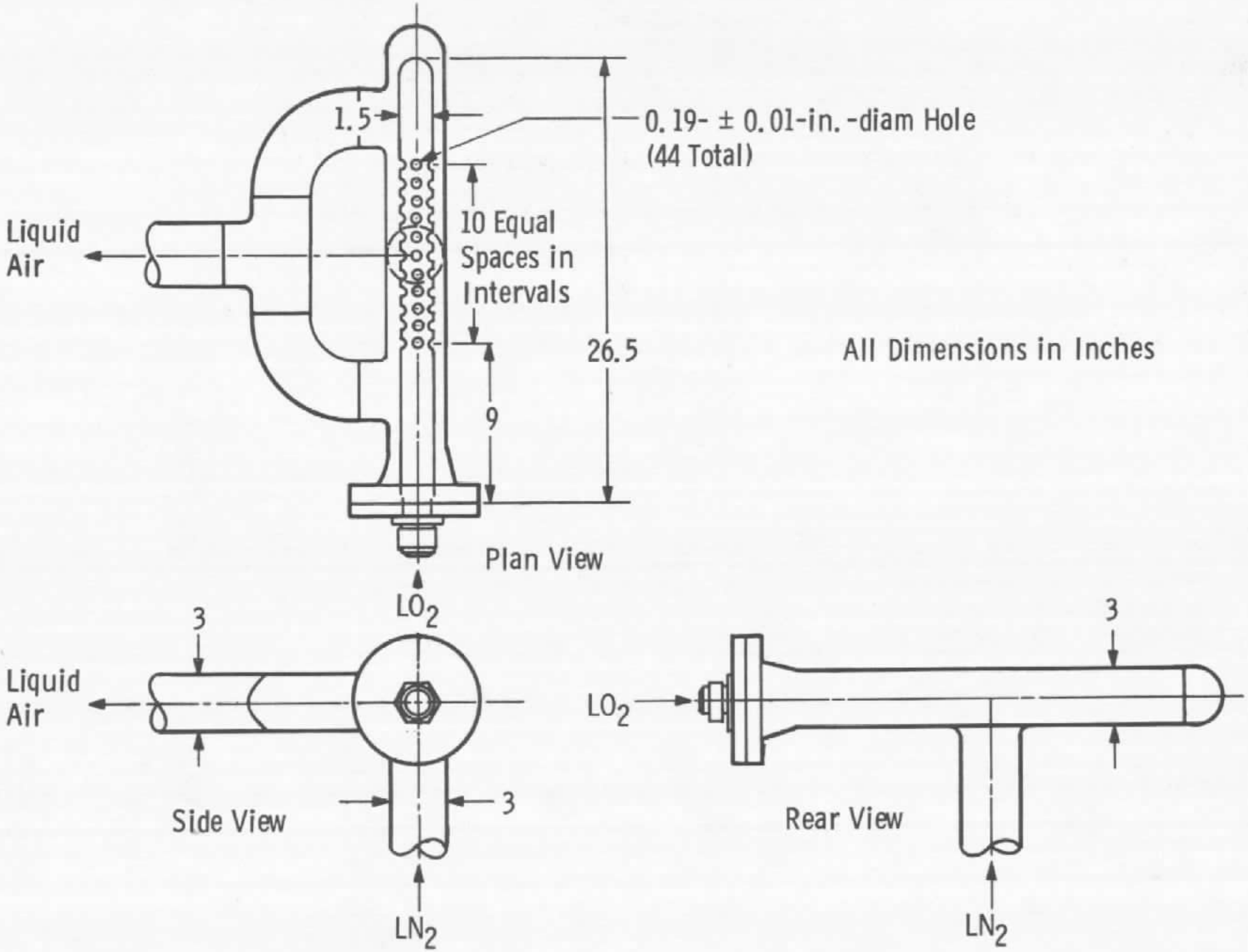


Fig. 5 Liquid Blender Schematic

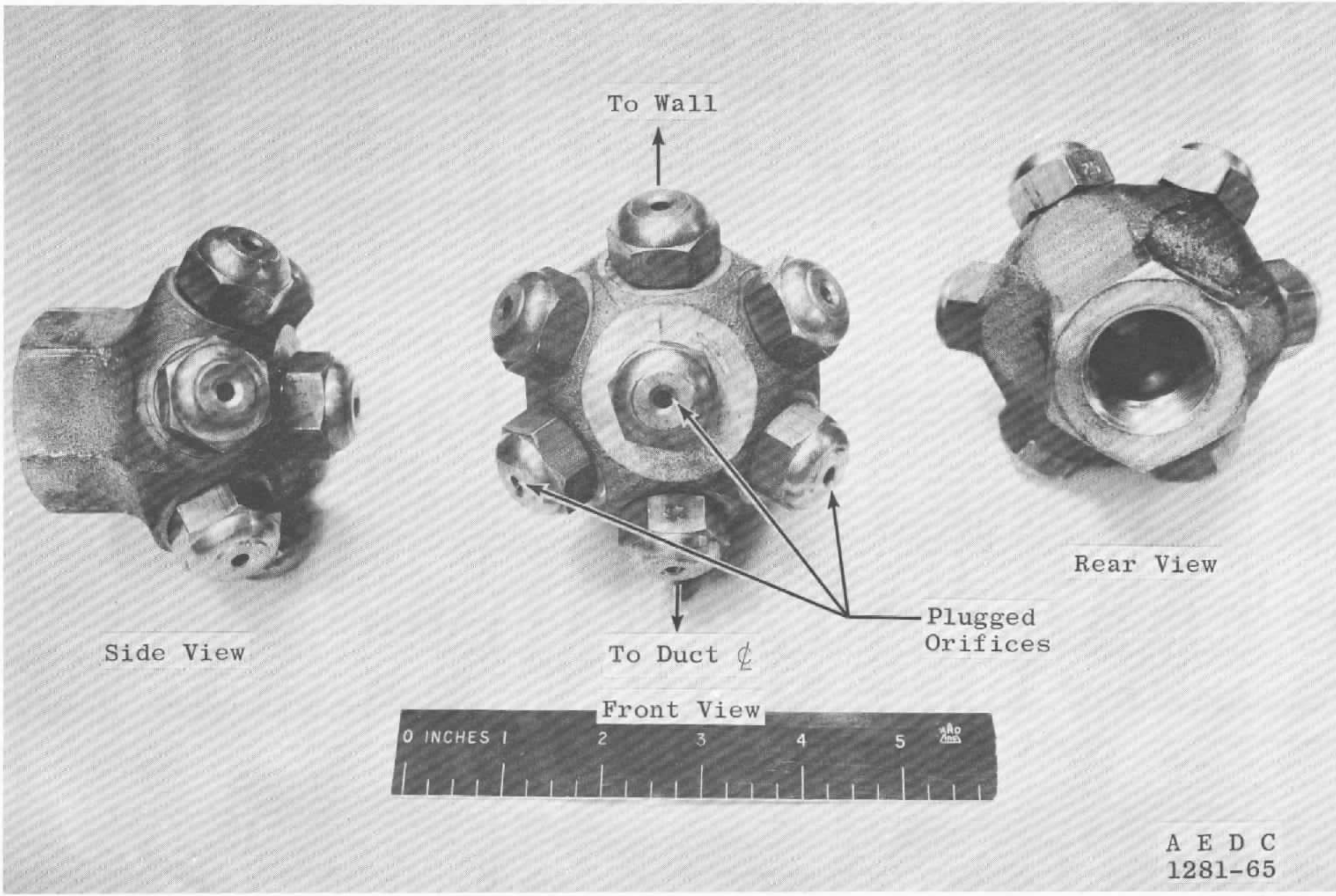
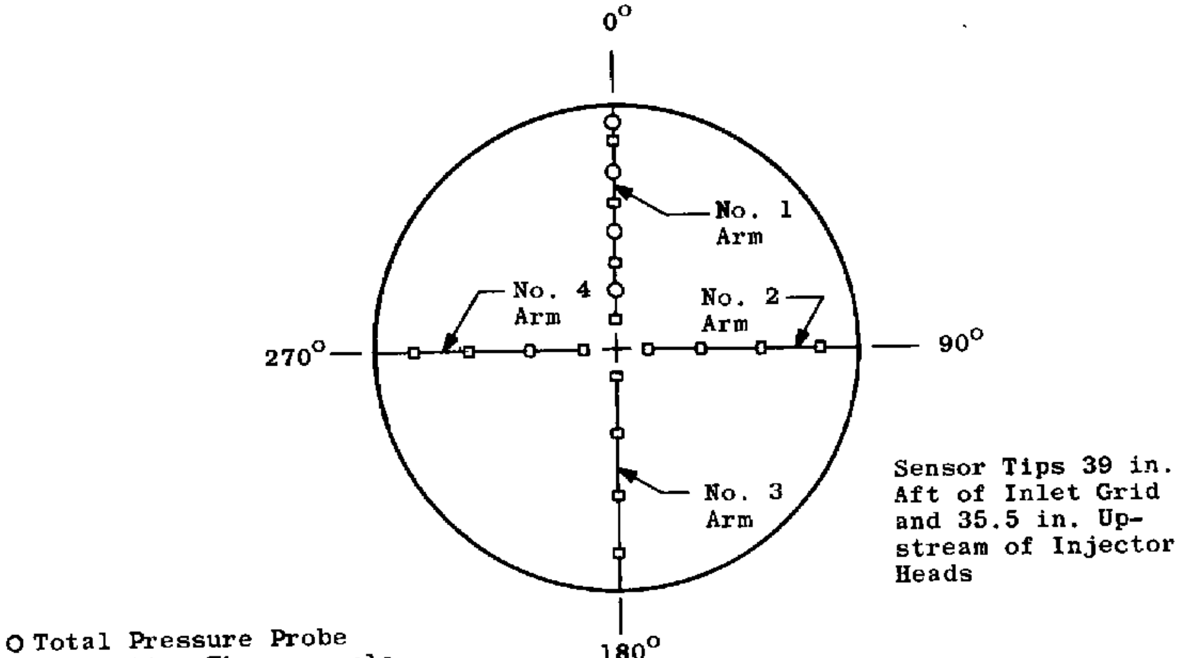
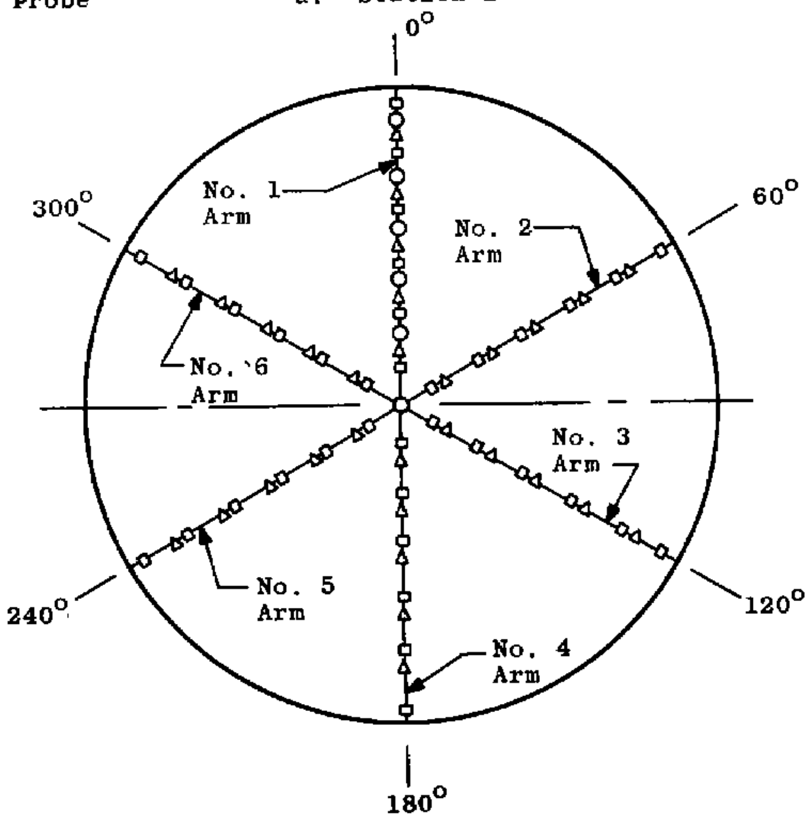


Fig. 6 Fogjet Nozzles

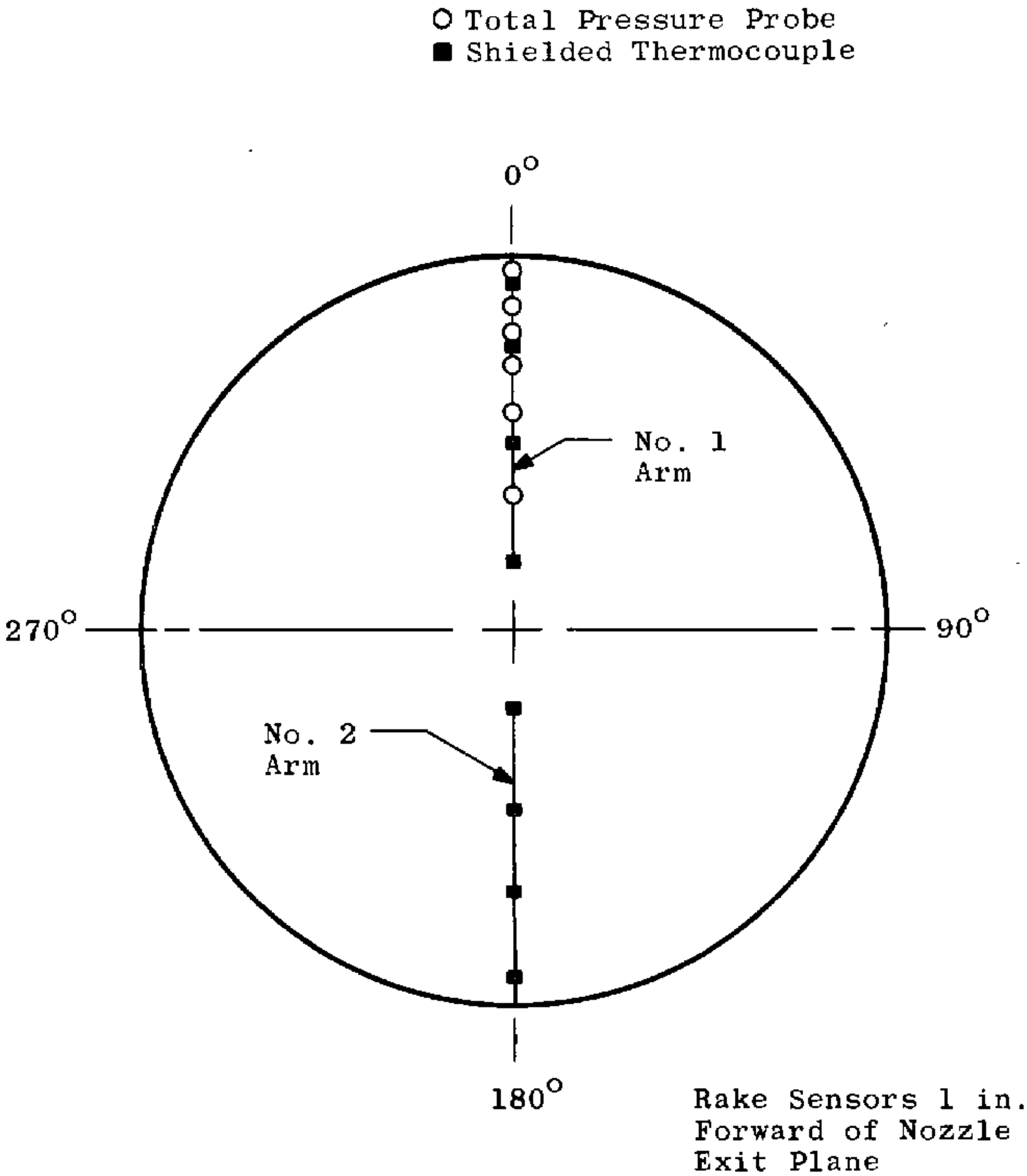


a. Station 1



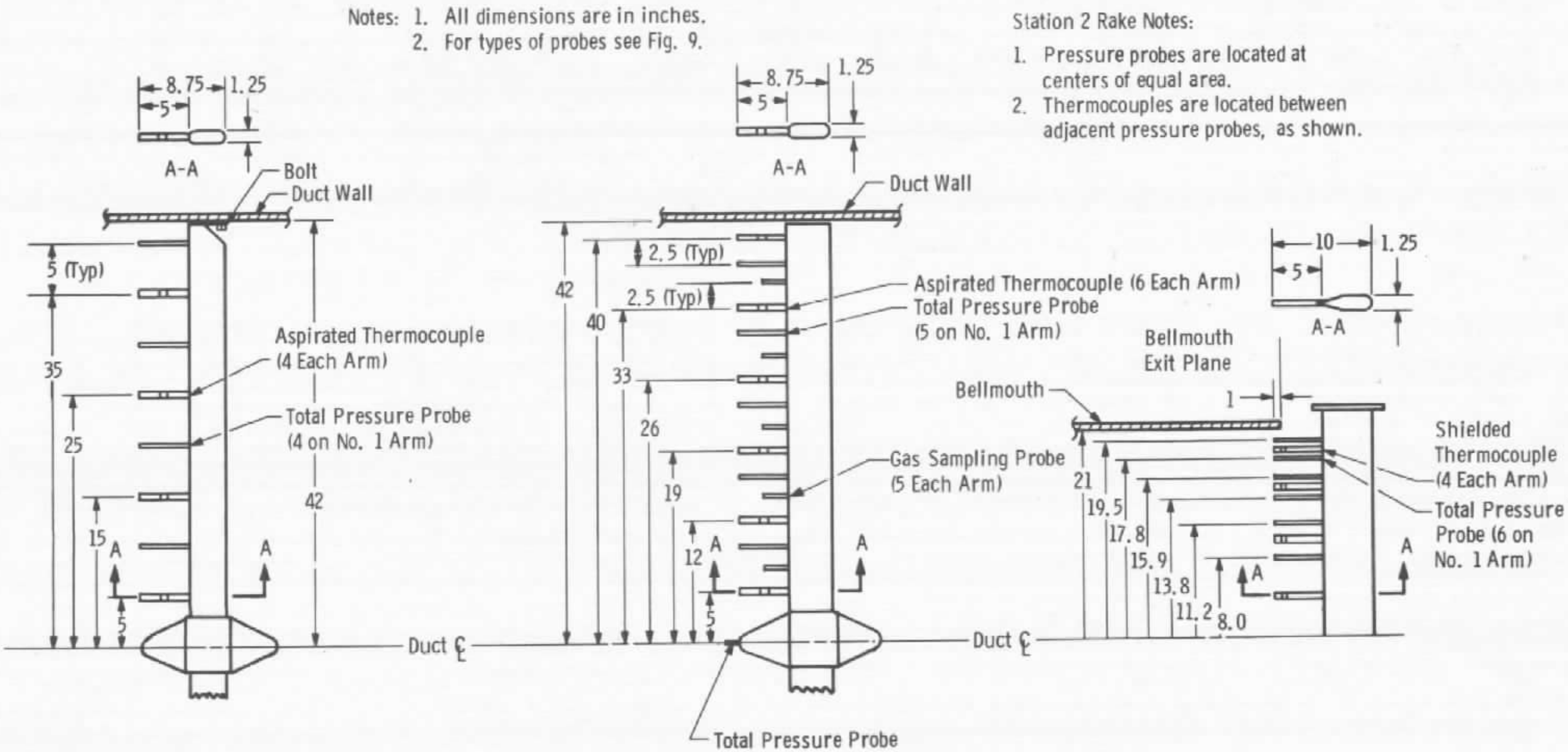
b. Station 1n

Fig. 7 Air Duct Instrumentation Details (Looking Upstream)



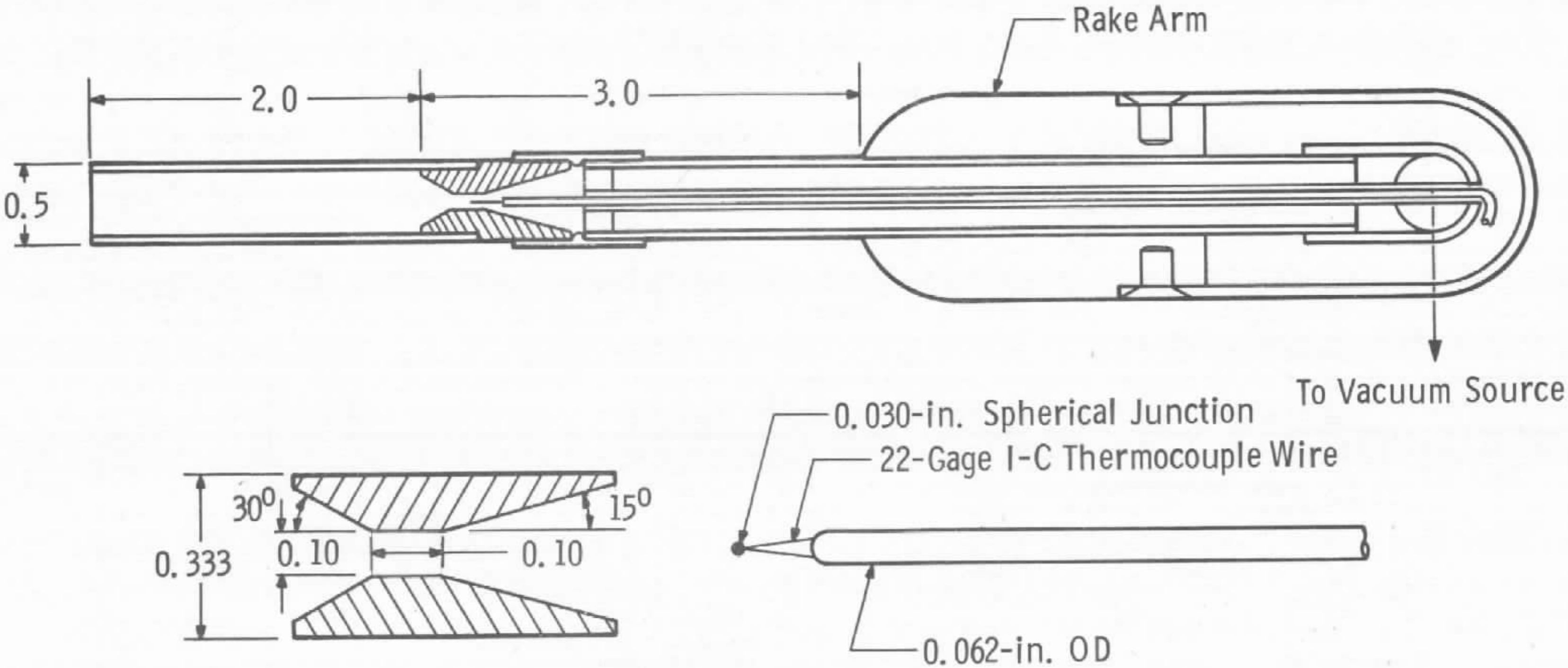
c. Station 2

Fig. 7 Concluded



a. Station 1 b. Station 1n c. Station 2

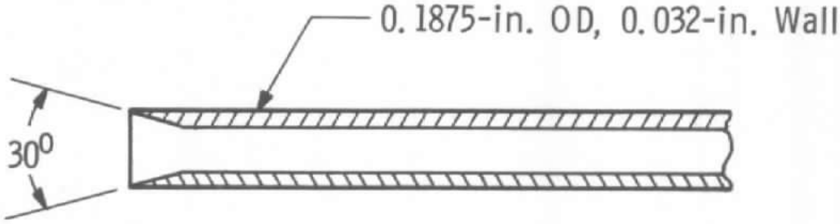
Fig. 8 Instrumented Rake Details



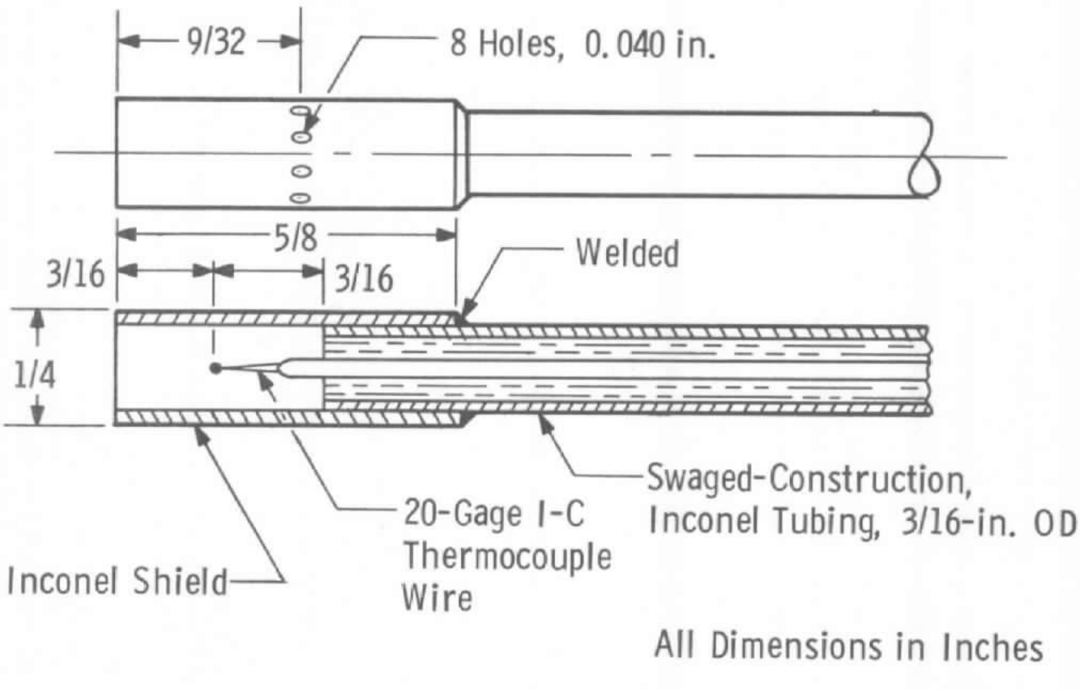
Notes: 1. The thermocouple junction must be centered in constant area section of the nozzle.
2. All dimensions are in inches.

a. Aspirated Thermocouple

Fig. 9 Probe Details



b. Total Pressure and Gas Sampling Probes



c. Shielded Thermocouple

Fig. 9 Concluded

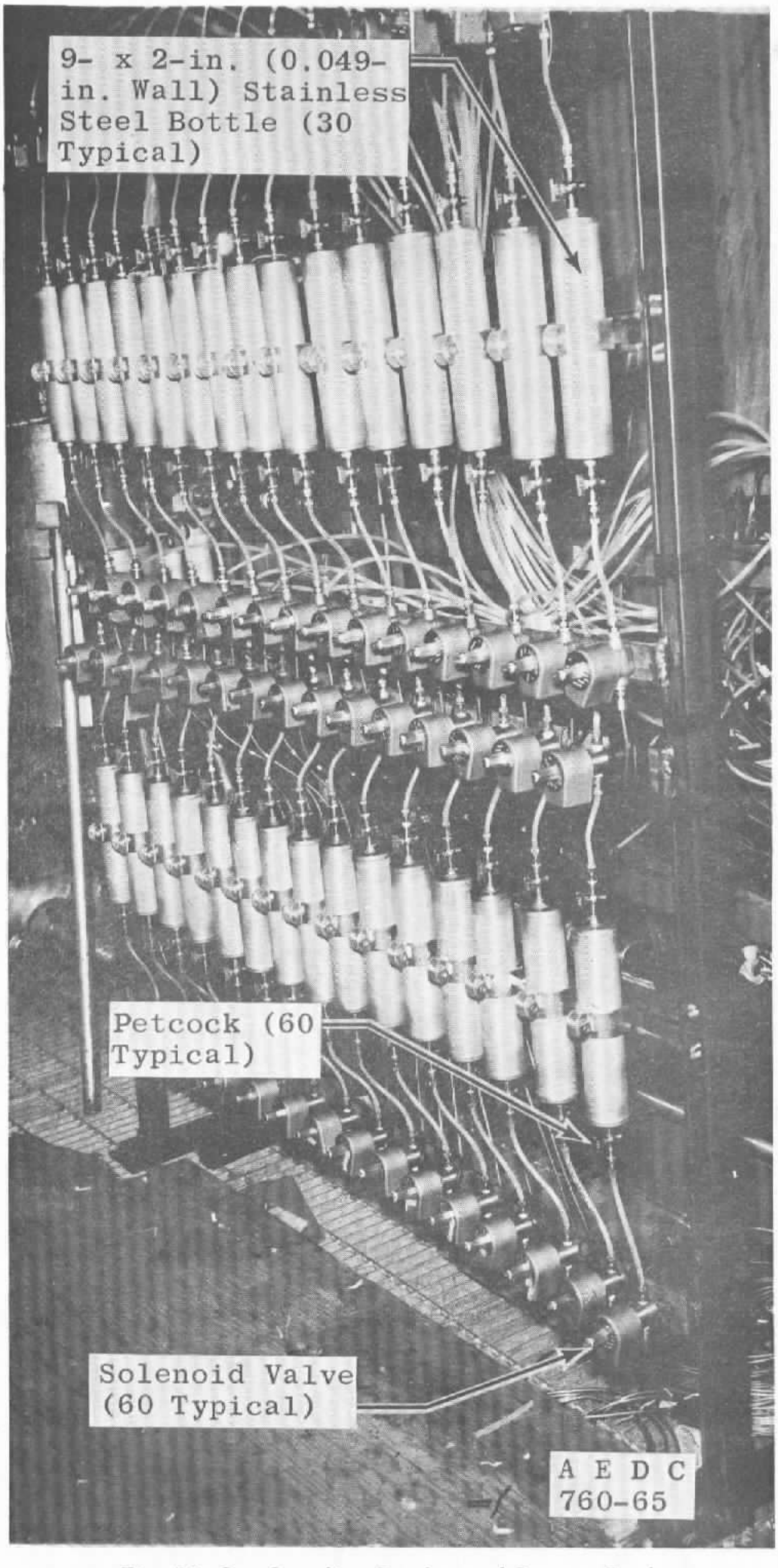
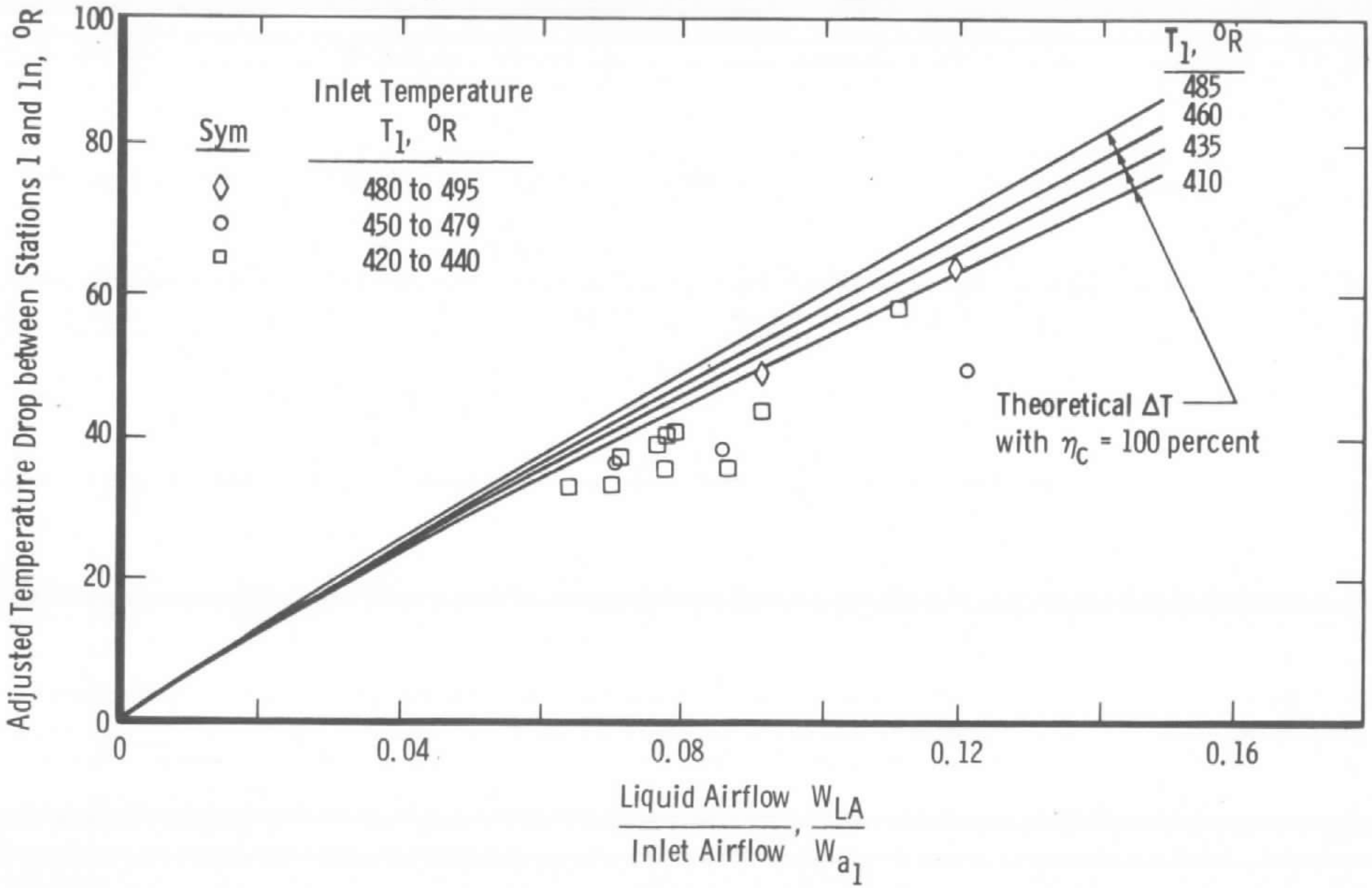
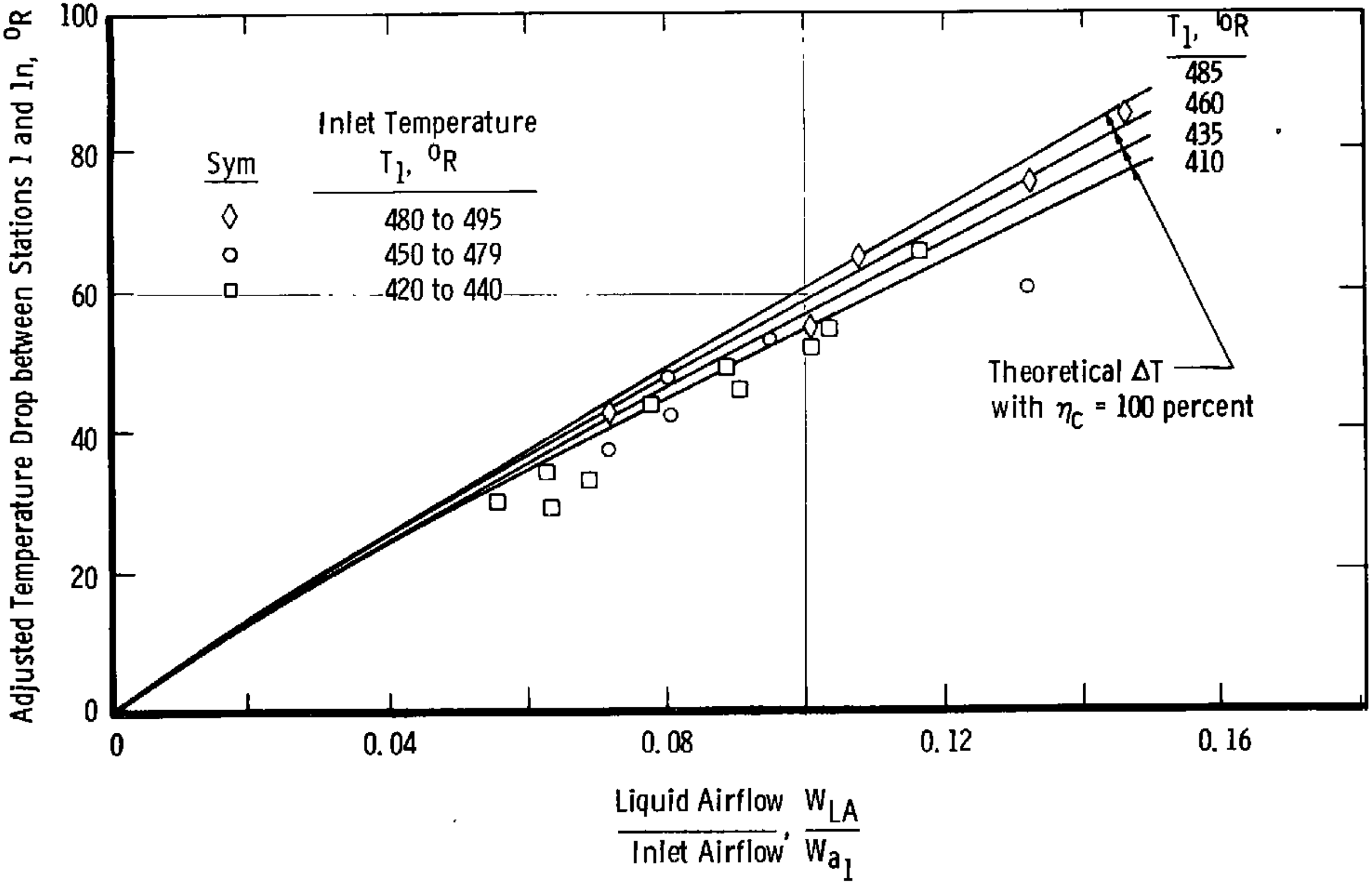


Fig. 10 Gas Sampling Bottles and Support Racks



a. Sampling Rake at 10-ft Location

Fig. 11 Airstream Cooling with Liquid Air Injection



b. Sampling Rake at 24-ft Location

Fig. 11 Concluded

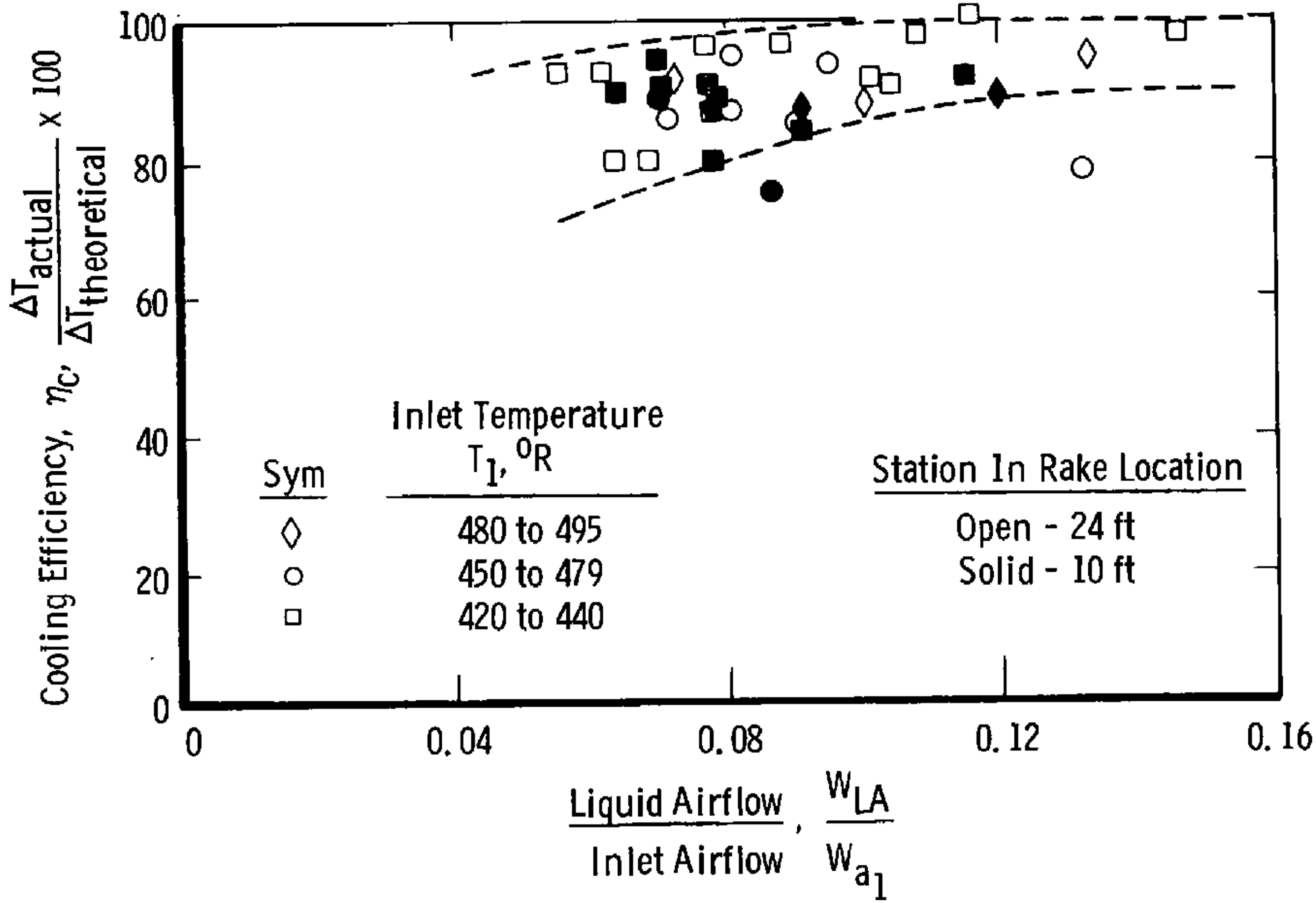


Fig. 12 Cooling Efficiency

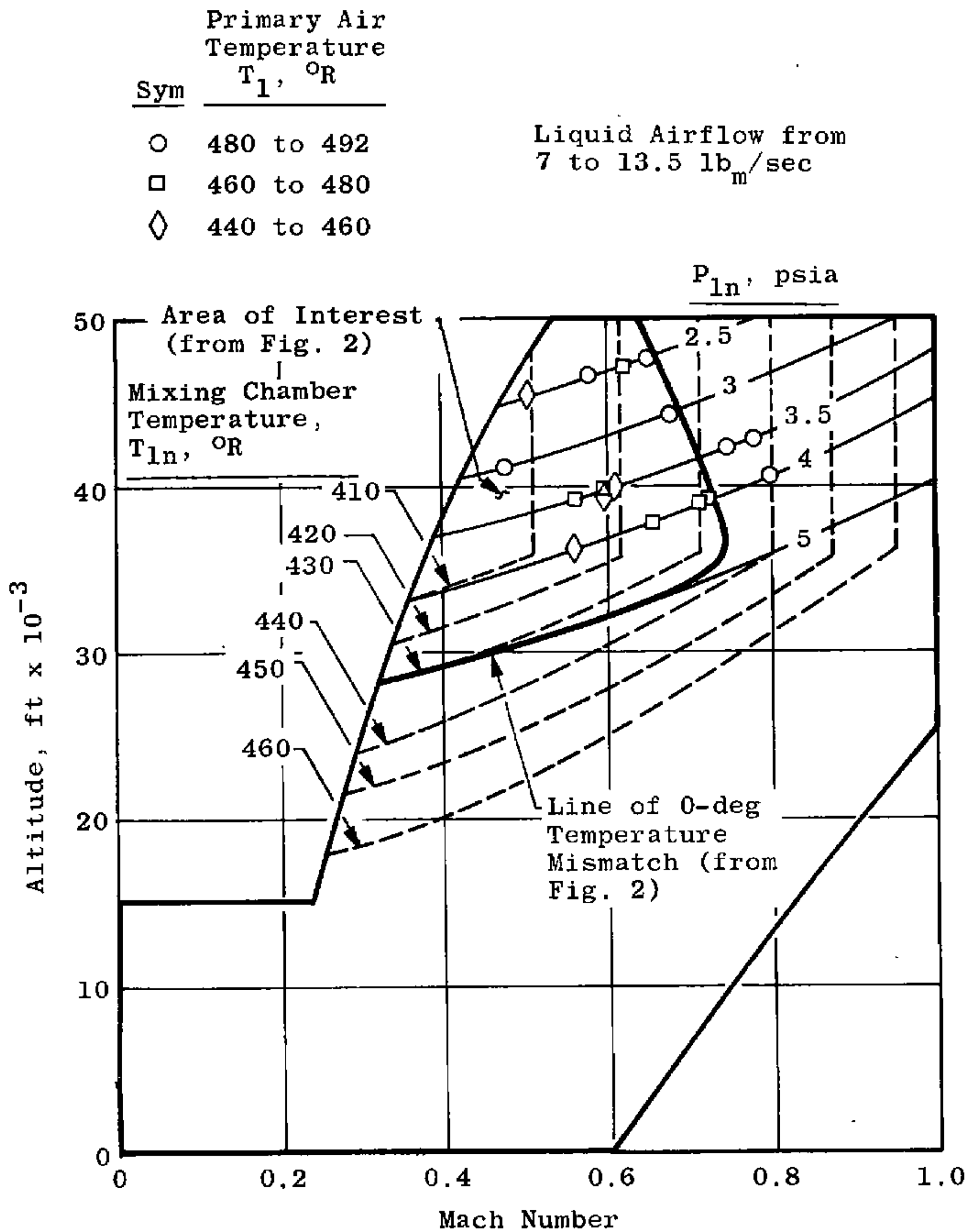


Fig. 13 Ram Temperature Simulation at Station 1n

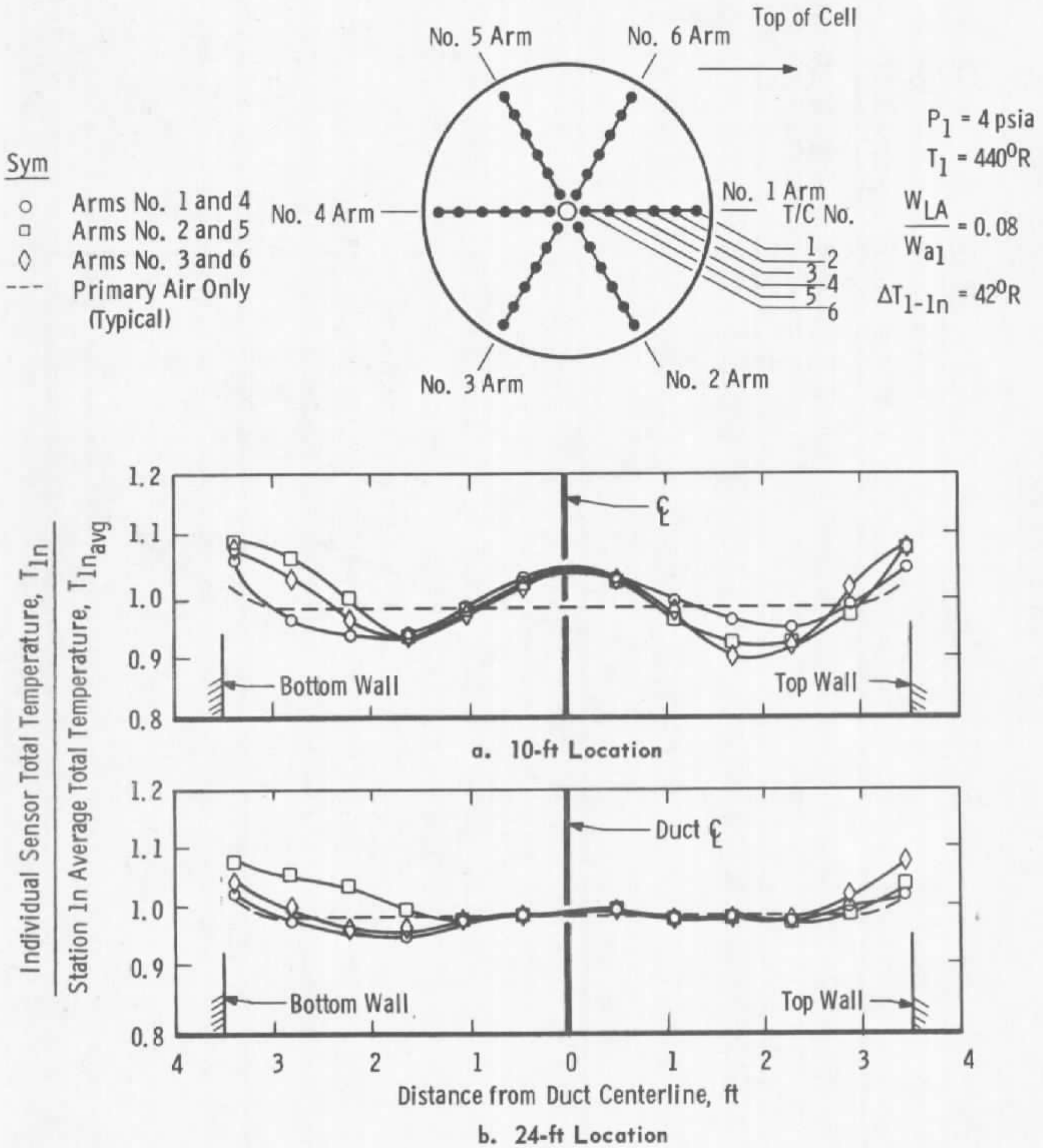


Fig. 14 Typical Radial Temperature Profiles along the Mixing Chamber

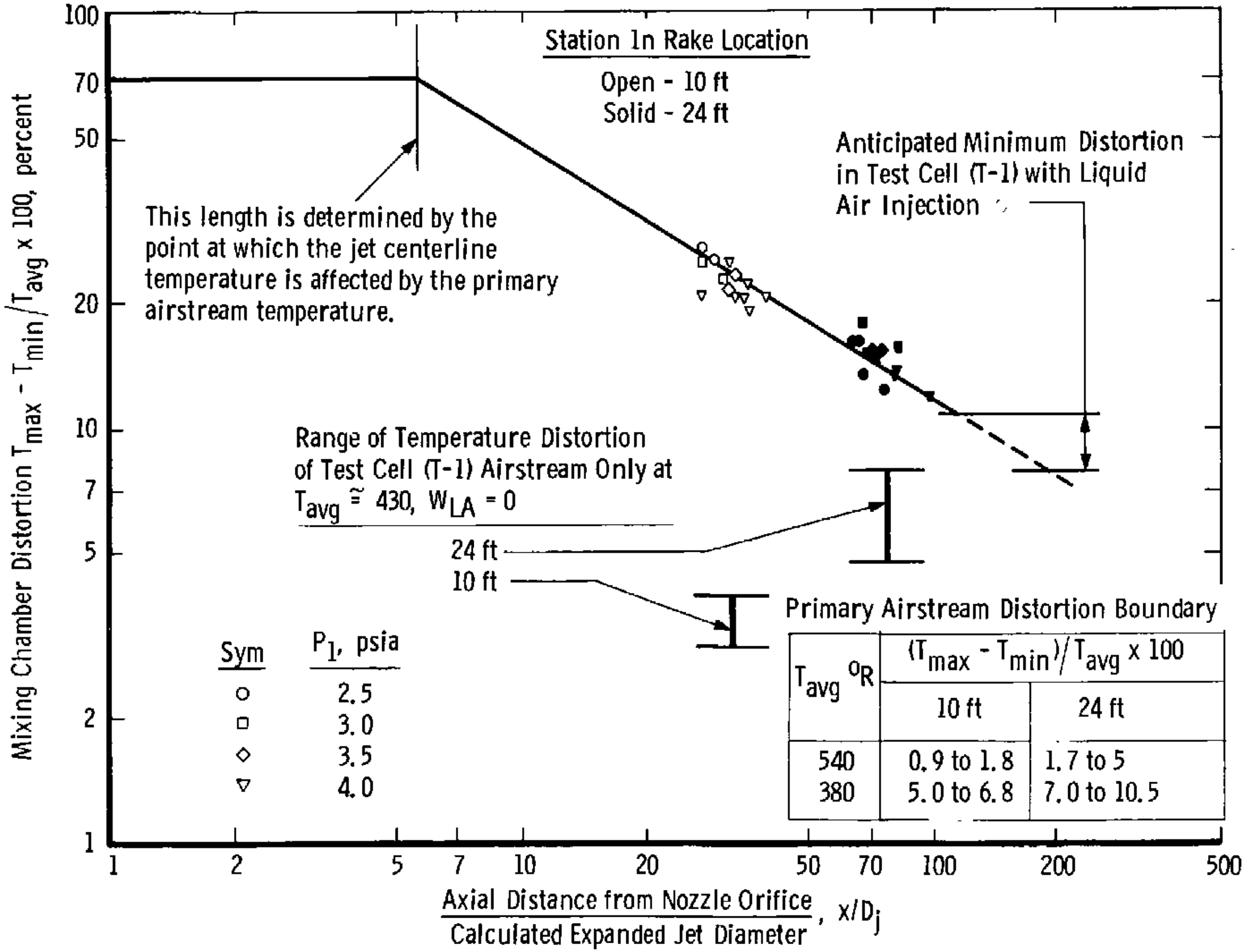
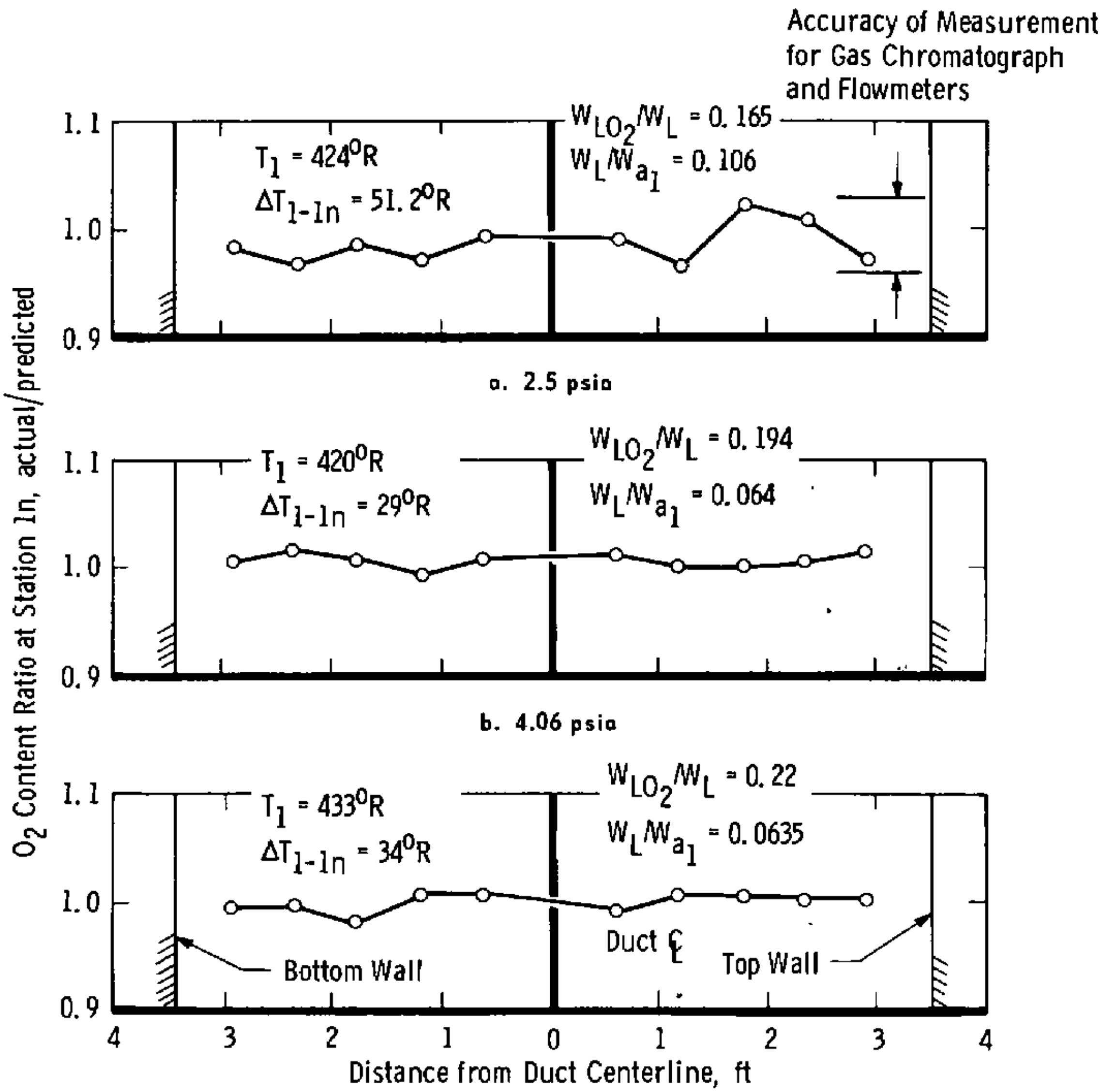


Fig. 15 Temperature Distortion along the Mixing Chamber



c. 5.09 psia

Fig. 16 Typical Gas Sample Profiles on Vertical Rake Arms Located at 24 ft as a Function of Mixing Chamber Pressure

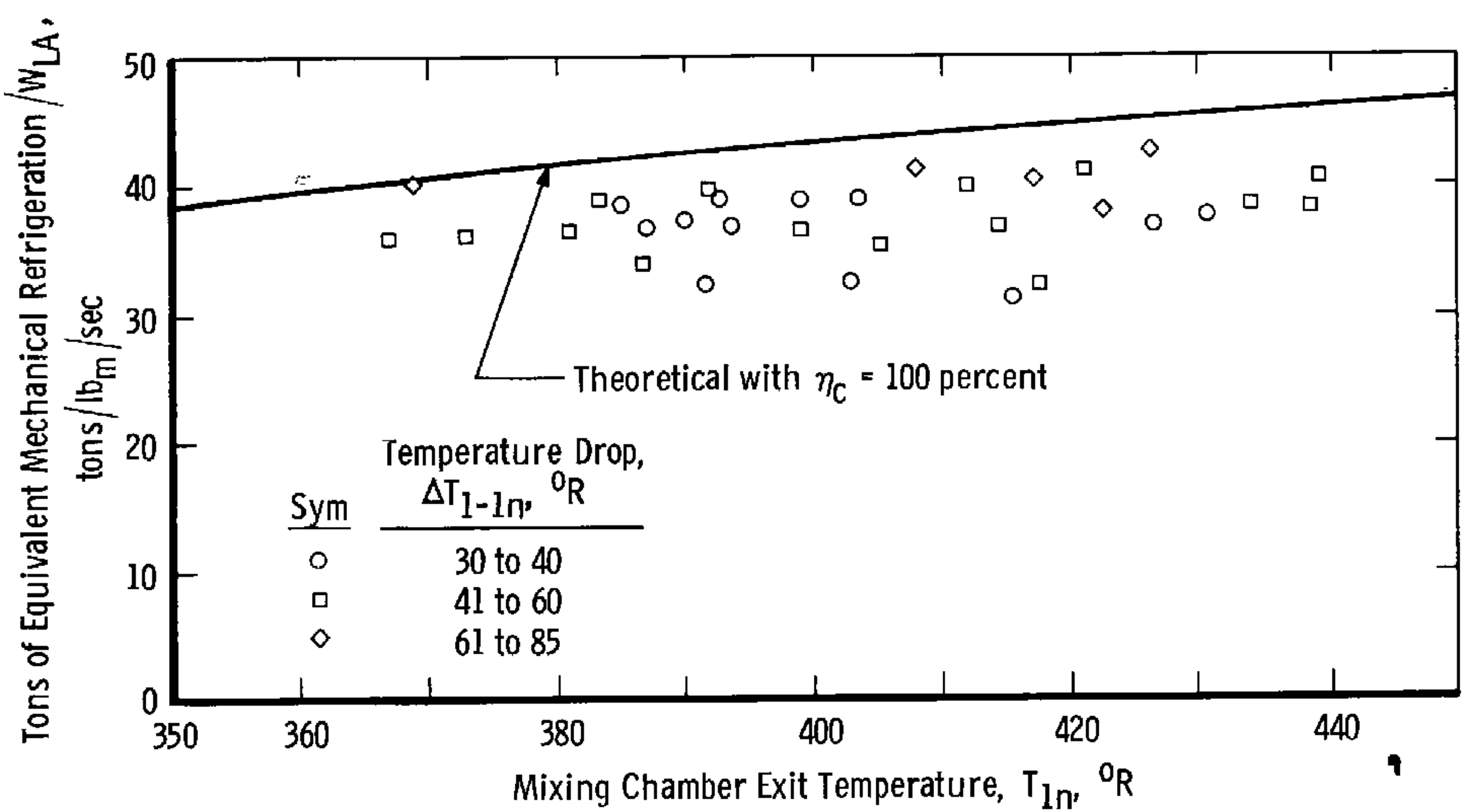


Fig. 17 Specific Equivalent Mechanical Refrigeration for Liquid Air Test Results

TABLE I
INSTRUMENTATION

Parameter	Measuring Device	Range of Measuring Device	Primary Recording Method*	Estimated Accuracy (~~Accuracy in percent of Full Scale~~)	Method of System Calibration
Duct, Plenum, and Cell Pressures	Manometer	0 to 120 in. Hg 0 to 120 in. H_2O	1	±0.05 in.	---
Duct Air Temperatures	Aspirating IC Thermocouple	370 to 540°R	2	±3°R	Known Millivolt Source and N.B.S. Temperature Table
Bellmouth Air Temperatures	Shielded IC Thermocouple	370 to 540°R	2	±3°R	
LN_2 Flows	Turbine-Type Flowmeter	4 to 40 lb_m/sec	2	±2.1 percent	Waterflow Calibration Stand Corrected for Specific Gravity of Fluids
LO_2 Flows		1 to 10 lb_m/sec	2	±1.6 percent	
Cryogenic System Pressures	Strain-Gage Transducers	0 to 60 psia 0 to 200 psia	3 4	±1 percent ±1 percent	Electrical Calibration at Levels of 15, 30, 50, and 65 psia
Cryogenic System Temperatures	IC Thermocouple	120 to 520°R	3 4 5	±3°R +5°R ±3°R	Known Millivolt Source and N.B.S. Temperature Table
Injector Manifold Temperatures	CC Thermocouples	120 to 520°R	3 4	±7°R ±8°R	
Duct Wall Temperature	IC Thermocouple	370 to 540°R	5	±3°R	

*1. Photographs
2. Magnetic Tape via Analog-to-Digital Converter
3. Continuous Direct-Inking, Null-Balance Potentiometer (Strip Chart)
4. Photographically Recording, Galvanometer-Type Oscillograph
5. Null-Balance Potentiometer

TABLE II
GAS SAMPLE ANALYSIS SUMMARY

	Sta. 1 - Duct Inlet			Cryogenics									Sta. 1n Duct Exit[1]		Predicted[4] O_2 Content at Sta. 1n, percent by volume
	Press., psia	Average Temp., °R	Airflow, lb/sec	Injector Inlet Press., atm	Injector Inlet Temp., °R	W_{LO_2}, lb/sec	W_{LN_2}, lb/sec	W_L, lb/sec	$\frac{W_{O_2}}{W_L}$	$\frac{W_{N_2}}{W_L}$	$\frac{W_L}{W_{a1}}$	Average Temp., °R	Rake Position, ft	
1	5.07	428	166	---	---	---	---	---	---	---	---	431	10	20.906
2	2.59	428	90	---	---	---	---	---	---	---	---	431		20.906
3	2.17	427	74	---	---	---	---	---	---	---	---	431		20.906
4	5.05	431	175	*2.83	161	2.31	9.88	12.19	0.190	0.81	0.0695	398	24	20.661
5	5.08	436	172	*2.63	159	1.27	5.49	6.76	0.188	0.812	0.039	404		20.758
6	5.09	433	180	*2.2	154	2.51	8.9	11.41	0.22	0.78	0.0635	402		20.846
7	5.08	433	178	*1.77	152	1.95	8.1	10.05	0.194	0.805	0.0565	406		20.727
8	5.06	436	170	---	---	---	---	---	---	---	---	443		20.906
9	5.05	425	174	**3.39	158	---	16.84	---	---	---	0.097	359		19.051
10	5.11	444	168	**3.96	159	---	9.75	---	---	---	0.058	415		19.736
11	4.03	435	135	---	---	---	---	---	---	---	---	443		20.906
12	4.06	420	135	2.92	159	1.68	6.96	8.64	0.194	0.806	0.064	396		20.699
13	3.0	419	108	1.82	174	1.09	---	---	---	---	0.0101	414		21.600
14	3.0	419	109	---	---	---	---	---	---	---	---	426		20.906
15	2.50	424	84	2.99	149	1.48	7.47	8.95	0.165	0.835	0.106	380		20.335
16	2.51	450	80.0	2.94	150	1.39	5.82	7.21	0.193	0.807	0.09	409		20.620
17	2.52	467	77.1	3.07	149	2.02	8.13	10.15	0.199	0.801	0.132	420		20.562
18	4.02	462	124	3.21	158	1.59	5.77	7.36	0.216	0.784	0.059	434		20.820
19	4.06	481	127.6	3.28	149	1.84	7.39	9.23	0.199	0.801	0.072	441		20.763
20	4.05	463	129.1	3.30	149	1.8	7.45	9.25	0.195	0.805	0.072	426		20.693
21	3.53	456	113.2	3.41	149	1.69	7.46	9.15	0.185	0.815	0.081	418		20.600
22	4.06	434	136.9	---	---	---	---	---	---	---	---	440	10	20.906
23	4.06	423	136.5	3.2	147	1.37	8.2	9.57	0.143	0.857	0.07	389		20.380
24	4.08	469	130.2	3.26	149	1.67	7.49	9.16	0.182	0.818	0.07	432		20.610
25	3.57	438	120.2	---	---	---	---	---	---	---	---	440		20.906
26	3.57	432	117.5	3.29	149	1.83	7.33	9.16	0.2	0.80	0.078	407		20.711
27	3.57	453	113.9	3.31	149	2.10	7.66	9.76	0.215	0.785	0.086	418		20.786
28	2.51	430	85.1	---	---	---	---	---	---	---	---	435		20.906
29	2.53	425	83.2	3.07	140	1.8	7.78	9.58	0.188	0.812	0.115	371		20.498

TABLE II (Continued)

	Sta. In Gas Sampling[2] - Arms[3] - Probes[3] - O_2/N_2 Concentrations, percent by volume																													
	Arm No. 1					Arm No. 2					Arm No. 3					Arm No. 4					Arm No. 5					Arm No. 6				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
1									20.9/77.6																					
2										21.0/78.3						20.8/77.8														
3											21.0/78.1																			20.7/78.0
4	21.0/78.4	21.0/78.7	21.0/78.1	20.9/78.1	21.0/78.1																									
5												21.1/78.1																	21.0/78.0	
6	20.9/78.1	20.9/78.1	21.0/78.2	21.0/78.2	20.7/77.8											20.7/77.2	20.8/78.1	20.4/78.1	21.0/78.1	21.0/78.2										
7														20.6/78.9													20.7/78.1			
8										21.1/78.8																				
9									19.9/79.5															20.2/79.8						
10															19.2/80.2											20.9/79.1				
11										21.2/78.4																				
12	21.0/78.9	20.8/78.5	20.7/78.3	20.7/78.6	21.0/78.9											20.8/78.4	21.0/79.2	20.8/78.9	20.5/78.4	20.8/78.7										
13							22.6/75.2																	22.6/75.2						
14								21.2/78.4															21.0/77.4							
15	19.7/79.2	20.5/78.9	20.8/78.1	19.7/78.7	20.0/79.2											19.9/79.6	19.6/78.6	20.0/79.2	19.7/77.2	20.2/78.9										
16											20.0/77.8	20.6/78.2	20.8/77.5	20.5/78.3	20.5/78.3															
17																					20.8/78.3	20.8/78.9	20.6/78.6	20.5/78.7	20.8/78.1					
18																											20.7/78.1		20.6/77.8	
19								20.7/78.7																						
20							20.8/78.4																							
21						20.4/77.9																								
22										20.7/78.7																				
23	20.7/78.0	20.0/78.4	20.0/78.0	20.3/79.2	20.4/78.0																									
24																20.5/78.8	20.4/78.4	20.3/78.4	20.3/77.7											
25									20.4/78.6																					
26											20.7/77.8	20.6/78.6		20.6/78.7	20.9/77.7															
27																					20.7/78.6	20.7/78.0	21.1/77.6	20.7/77.1	20.6/78.3					
28								20.8/78.5																						
29																										20.2/79.2	20.2/79.0	19.6/79.1	20.6/78.1	20.9/77.9

TABLE II (Continued)

	Sta. 1 - Duct Inlet			Cryogenics								Sta. 1n Duct Exit[1]		Predicted[4] O_2 Content at Sta. 1n, percent by volume
	Press., psia	Average Temp., °R	Airflow, lb/sec	Injector Inlet Press., atm	Injector Inlet Temp., °R	W_{LO_2}, lb/sec	W_{LN_2}, lb/sec	W_L, lb/sec	$\frac{W_{O_2}}{W_L}$	$\frac{W_{N_2}}{W_L}$	$\frac{W_L}{W_{a1}}$	Average Temp., °R	Rake Position, ft	
1	2.53	486	78	3.12	146	1.76	7.58	9.34	0.188	0.812	0.12	422	10	20.489
2	2.53	445	81.9	3.14	143	1.63	7.18	8.81	0.185	0.815	0.108	392		20.498
3	4.12	422	136	3.38	173	3.47	8.38	11.85	0.293	0.707	0.087	391		21.358
4	4.11	439	135	3.41	170	2.44	8.29	10.73	0.227	0.773	0.079	402		20.887
5	4.11	438	131	2.73	193	1.73	7.19	8.92	0.194	0.806	0.068	435		20.688
6	4.11	427	137	3.04	170	2.41	8.22	10.63	0.227	0.773	0.077	390		20.869
7	4.11	427	137	3.09	170	2.06	7.73	9.79	0.210	0.790	0.071	393		20.779
8	4.12	426	138	2.78	170	1.80	7.07	8.87	0.203	0.797	0.064	396		20.752
9	4.11	428	139	2.49	198	5.68	---	5.68	---	---	0.041	411		23.702
10	4.11	428	139	2.50	198	4.16	---	4.16	---	---	0.030	413		22.915
11	4.09	429	125	2.19	198	2.56	---	2.56	---	---	0.020	419		22.299
12	4.03	438	131	2.68	165	2.12	8.13	10.25	0.207	0.793	0.078	408		20.743
13	4.00	439	135	---	---	---	---	---	---	---	---	443		20.933
14	4.03	441	129	3.84	170	2.40	8.80	11.20	0.214	0.786	0.087	414		20.788
15	3.51	430	112	3.93	170	2.25	8.02	10.27	0.219	0.781	0.092	389		20.824
16	3.53	467	107	4.01	170	2.75	10.16	12.91	0.213	0.787	0.121	419		20.770
17	3.54	488	107	3.94	170	2.15	7.71	9.86	0.218	0.782	0.092	438		20.797
18	4.05	437	135	3.18	176	---	8.22	---	---	---	0.061	400	24	19.720
19	4.06	435	134	3.47	176	2.32	8.02	10.34	0.224	0.776	0.077	397		20.924
20	4.06	467	129	3.46	176	2.24	8.16	10.40	0.215	0.785	0.081	423		20.797
21	3.50	465	111	3.18	177	2.26	8.24	10.50	0.215	0.785	0.085	415		20.815
22	2.49	434	82	3.13	178	2.03	7.48	9.51	0.214	0.786	0.116	373		20.779
23	2.49	492	76	3.33	179	2.29	7.85	10.14	0.226	0.774	0.133	417		20.842
24	3.51	488	108	3.35	179	2.30	8.62	10.92	0.211	0.789	0.101	434		20.724
25	3.51	432	116	3.40	178	2.23	8.02	10.25	0.218	0.782	0.088	389		20.833
26	3.02	434	99	3.53	178	2.23	8.05	10.28	0.217	0.783	0.104	385		20.776
27	3.03	490	94	3.39	179	2.25	7.84	10.09	0.223	0.777	0.107	426		20.851

Notes: 1. Pressure at Sta. 1n similar to that at Sta. 1, within accuracy of measurement
2. Gas sample accuracy of measurement ±0.5 percentage points of readings
3. Sta. 1n rake

a. View looking upstream
b. Numbers shown are that of the arms.
c. No. 1 probe near wall; no. 5 probe near center hub (see Figs. 7b and 8b)

4. Based on oxygen mass addition
5. Number of open orifices/nozzle other than the four orifices used for ΔT determination, shown in Fig. 6
*5
**3

TABLE II (Concluded)

	Sta. 1n Gas Sampling - Arms - Probes - O_2/N_2 Concentrations, percent by volume																													
	Arm No. 1					Arm No. 2					Arm No. 3					Arm No. 4					Arm No. 5					Arm No. 6				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
1							19.8/79.0																							
2						20.7/78.0																								
3	20.2/79.1	20.0/80.0	20.8/78.2																											
4				21.3/77.5	20.9/77.8	20.9/77.9																								
5							21.5/77.9	21.3/78.1	21.5/77.6																					
6											21.4/78.1	21.1/77.6																		
7														20.8/78.1	21.2/77.9															
8																20.9/78.1		20.6/77.6	20.8/78.1	21.1/77.9										
9																								26.1/73.2	24.0/75.0					
10																										20.8/78.1	24.9/74.7			
11																												23.9/73.8	23.0/76.0	
12	20.1/79.2	19.2/79.9	19.3/79.8	20.0/79.0																										
13																														20.9/78.1
14						20.8/78.1						21.4/78.1						20.8/78.3												
15																20.9/78.1						20.8/78.3								
16											20.9/78.6						19.9/78.1						20.9/78.1							
17								20.3/78.4	20.6/78.6																					
18	19.5/78.7						19.2/79.7																							
19		20.8/78.1						20.5/77.6						19.3/78.3																
20			20.7/77.5						20.7/78.7						19.4/78.7															
21				20.5/77.5						20.9/78.3						20.5/78.1														
22					20.7/78.0						20.8/79.0						20.5/78.1													
23						20.5/78.0						20.9/78.8						20.6/78.0												
24																			20.5/78.9				20.8/78.0				20.9/78.1			
25																				20.3/78.1				20.9/78.0				21.0/79.0		
26																					20.5/77.2				20.7/78.0				20.8/78.0	
27																						20.5/77.8								

APPENDIX I
THERMODYNAMICS OF LIQUID AIR INJECTION

The cooling of an airstream by the injection of liquid air occurs in two separate cooling modes, evaporation and aerodynamic mixing. Evaporation involves the transfer of heat from the airstream to the liquid air in a quantity equal to the latent heat of vaporization of the liquid air, which is a function of storage pressure as shown on a pressure-enthalpy plot for air (Fig. I-1).

The liquid air components stabilize at a condition corresponding to a point on the saturated liquid line during pre-test storage (1 atm, point 1). When the pressure surrounding the liquid is increased, the fluid is compressed at constant temperature to point 2. Two alternatives exist at this point. If the fluid is used immediately by injection into the primary airstream, it follows a line of constant enthalpy (throttling process) to the pressure existing in the primary airstream after injection. The fluid then vaporizes at constant pressure and follows an undefined process to its final state (point 5). If, however, the fluid is left in tankage under pressure for a period of time, heat is transferred to the fluid at constant pressure until point 2' is reached. From this point the fluid is throttled to point 3' and from that point follows the same process outlined above.

The enthalpy gain for process 2-3-4-5 is greater than that for process 2'-3'-4-5 by the amount defined by 3-3'. This indicates that long storage periods tend to reduce cooling performance. The utilization of high tank pressures to reduce cavitation problems will result in a very slight deterioration in the theoretical performance of a liquid air injection system for the initial pressure shown. The deterioration is the amount of H_1-H_2.

The amount of cooling (enthalpy change) of the primary airstream is primarily dependent on the initial states of the liquid air (in storage) and the primary airstream. It has a slight dependency on the tank pressure (point 2) as shown in Fig. I-1.

The liquid system reported herein used high pressure only on the LO_2 tank. The thermodynamics of such a process which combines LO_2 and LN_2 is similar to that described above for liquid air.

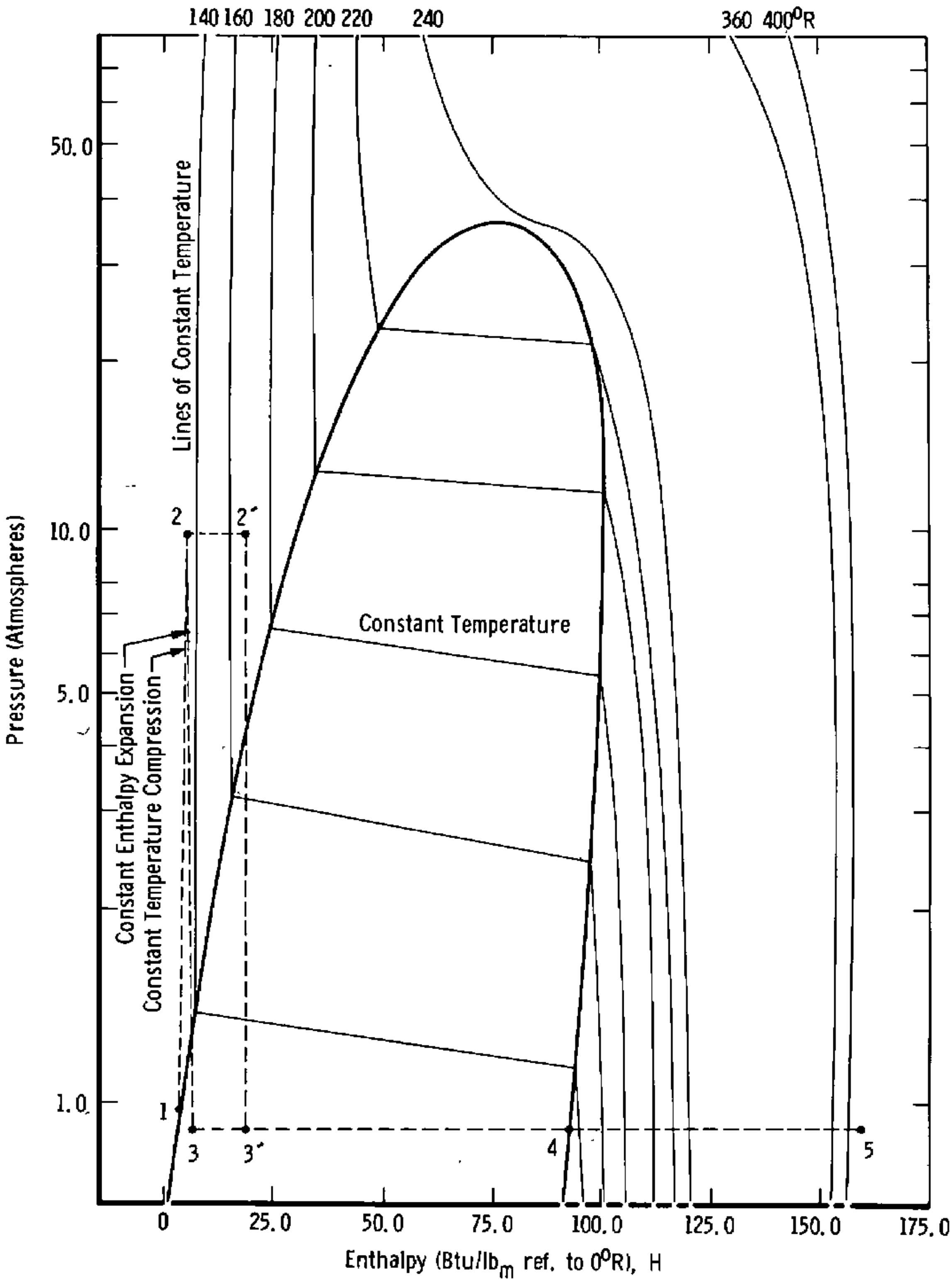


Fig. I-1 Pressure-Enthalpy Curve for Air

APPENDIX II
METHODS OF CALCULATION

General methods and equations used to compute the parameters presented in this report are given below. Where applicable, the arithmetic average of pressures and indicated temperatures were used.

SPECIFIC HEAT

The specific heat at constant pressure of gaseous air was calculated from the empirical equation

$$c_p = 0.2318 + 0.104 \times 10^{-4}\, T + 0.7166 \times 10^{-8}\, (T)^2$$

The specific heat at constant pressure of liquid air was assumed to be constant at 0.2393.

The ratio of specific heats was determined from

$$\gamma = c_p / c_v$$

where

$$c_v = c_p - R/J$$

TEMPERATURES

Airstream total temperature was calculated by applying a recovery factor to the indicated temperature according to the following equation:

$$T = \frac{T_i}{\left(\frac{p}{P}\right)^{\frac{\gamma-1}{\gamma}} + RF\left[1 - \left(\frac{p}{P}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

where

$$RF = 0.93 \text{ (stations 1 and 1n)}$$

$$= 0.95 \text{ (station 2)}$$

AIRFLOW

Airflow at station 2 (choked bellmouth) was calculated from the following equation:

$$W_{a_2} = P_2\, A_2\, C_{f_2} \sqrt{\frac{\gamma g}{RT_2}} \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}$$

where

$$C_{f_2} = 0.99$$

Liquid flow was calculated as follows:

$$W_L = W_{LN_2} + W_{LO_2}$$

where the LN_2 and LO_2 flow rates were measured using turbine-type flowmeters.

Primary airflow (W_{a1}) was calculated as follows:

$$W_{a_1} = W_{a_2} - W_L$$

The air extracted through the 30 gas sampling probes (0.0065 percent of the total) and through the 52 sonic aspirating thermocouple probes (0.03 percent of the total) was considered negligible.

THEORETICAL TEMPERATURE

The theoretical gas temperature that could be obtained at station 1n with 100-percent evaporation and complete mixing of the injected liquid air was calculated from the following heat energy balance relationship obtained by assuming an adiabatic system:

$$T_{1n_{th}} = \frac{-H_v W_{LA} + c_{p_{LA}} W_{LA} T_{LA} + W_{a_1} c_{p_1} T_1}{c_{p_{1n}} W_{a_{1n}}}, \ ^\circ R$$

H_v = Latent heat of vaporization of liquid air at 1 atm pressure (88.2 Btu/lb_m)

T_{LA} = Temperature of saturated liquid air vapor at 1 atm pressure (142°R)

$W_{a_{1n}}$ = W_{a_2} (assumes no leakage between stations 1n and 2)

WEIGHTED TOTAL TEMPERATURES

The weighted average of total temperatures at measuring stations 1 and 1n were obtained as follows:

$$T = \sum_{i=1}^{n} C_i T_i$$

where

$$C_1 = \frac{A_1}{A_t} \quad C_2 = \frac{A_2}{A_t} \quad --- \quad C_n = \frac{A_n}{A_t}$$

for which A_1, A_2---A_n are the areas sensed by each thermocouple under consideration, A_t is the total cross-sectional area, and T_1, T_2 --- T_n are the total temperatures for the relative selected areas A_1, A_2 --- A_n.

WALL HEAT SOURCE EFFECTS

The existence of a temperature differential (ΔT) between the airstream and the chamber inner walls caused a heat flux to be established which warmed the airstream as it proceeded down the chamber. The flux resulted from the walls acting as a heat source rather than from heat transfer from ambient conditions through the walls.

Temperature measurements at station 1n were adjusted for the heating described above by the use of an empirical plot (Fig. II-1) of the temperature differential

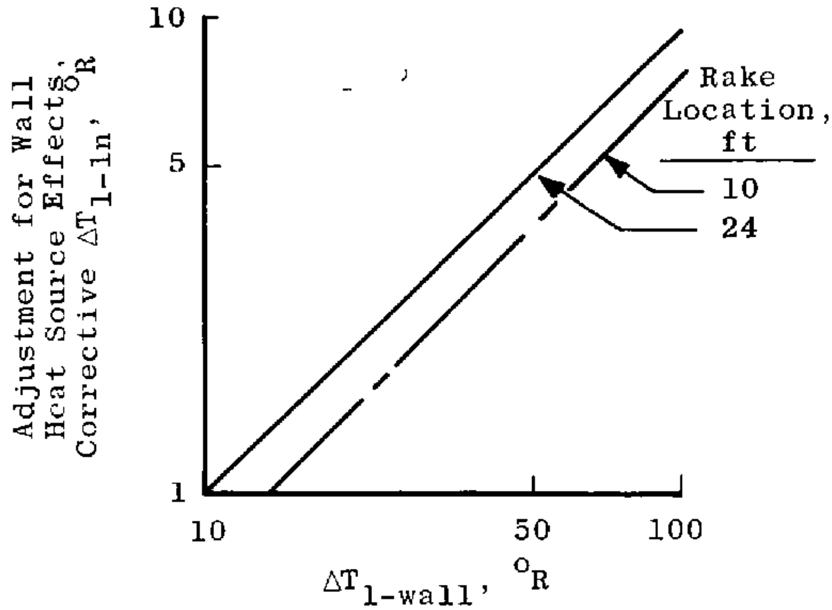


Fig. II-1 Duct Wall Heat Source Correction

between the wall and the primary airflow ($\Delta T_{1\text{-wall}}$) and the temperature differential between stations 1 and 1n (corrective ΔT_{1-1n}) obtained for various inlet conditions with zero liquid airflow. The adjusted temperature drop due to liquid air injection was obtained from:

$$\text{Adjusted } \Delta T_{1-1n} = \text{Measured } \Delta T_{1-1n} + \text{Corrective } \Delta T_{1-1n}$$

COOLING EFFICIENCY

Cooling efficiency at station 1n was defined as

$$\eta_c = \frac{\text{Adjusted } \Delta T_{1-1n}}{T_1 - T_{1n_{th}}} \times 100, \text{ percent}$$

TEMPERATURE DISTORTION

The mixing chamber temperature distortion is expressed as percent distortion and is determined as follows:

$$\text{Percent distortion} = \frac{T_{max} - T_{min}}{T_{avg}} \times 100$$

where

T_{max} = maximum indicated total temperature

T_{min} = minimum indicated total temperature

T_{avg} = numerical average of the 30 total temperature probes

MIXING LENGTH PARAMETER

The dimensionless mixing length parameter, x/D_j, is defined as follows:

x = axial location in the mixing chamber from nozzle orifice, ft (measured)

D_j = expanded jet diameter for each injector nozzle orifice, ft (from continuity equation)

$$D_j = \frac{1}{12}\sqrt{\frac{4}{\pi}\,\frac{(W_{LA}/N)\,R\,T_{LA}}{p_1\,V_1}}$$

where

N = total number of injector orifices (20)

V_1 = 100 ft/sec (assumed constant)

$$D_j = \frac{1}{12}\sqrt{\frac{4}{\pi}\left(\frac{w_{LA}}{w_1}\right)\left(\frac{A_1}{N}\right)\left(\frac{T_{LA}}{T_1}\right)}$$

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13 ABSTRACT

An investigation was conducted to determine the feasibility of producing a low temperature, uncontaminated airstream by injection of liquid air into a primary airstream. Steady-state data were obtained with primary airflow conditions generally set at total pressures from 2.5 to 5 psia and supply air temperatures ranging from 380 to 540°R. Liquid airflow rates ranged from 0 to 13.5 lb/sec. Temperature drops of the primary airstream up to 85°R were recorded with liquid air-to-primary air ratios up to 0.146. Calculated cooling efficiencies ranged from 75 to 100 percent. Gas samples obtained in the mixing chamber at locations 10 and 24 ft downstream from the injection station indicated that the gas flow was a homogeneous mixture with the O_2 and N_2 content of the gas samples dependent upon the proportions injected.

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